University of Alberta

High School Students' Enactment of Chemistry Knowing in Open-entry Laboratory Investigations

by

Sentsetsa M. Pilane ©

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment
of the requirements for the degree of Doctor of Philosophy

Department of Secondary Education

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Dedication

This work is dedicated to:

my late mom and dad, Maria Dikeledi Pilane and Thari Ofentse Pilane
my aunts, Dr. Ellen Kate Kuzwayo and Mrs. Emma Mmutsi Mabokela
my mother-in–law, Madame Ludy Quist
my husband, Keli Tamaklo
our children Kelebogile, Oratile, Thato, Karabo, Sechaba, and Duncan
my brothers and sisters and their families, and to all who have touched my life in the many different and special ways.

There are two Setswana proverbs or sayings which, when taken jointly, resonate with my understanding of some of the basic principles encapsulated in enactivist ideas of cognition or learning. These proverbs existed from my history and helped me as I grappled with some of the ideas of enactivism. These sayings have a deep meaning in Setswana which can not be translated easily into English.

"Moremogolo go betlwa wa taola, wa motho o a ipetla."

This could be equivalent to saying that human greatness or uniqueness is not handed on a silver platter; rather it is carved from within oneself.

"Motho ke motho ka ba bangwe"
This second saying is common to all the different Southern African languages and can be translated literally as "A person is a person through other people" (Kuzwayo 1998, p. 29).
Kuzwayo elaborating on the meaning of the saying said that it means that "A person becomes human through his or her interaction with other people," and that this saying could be equivalent to the English saying that "no man is an island." (p. 29)

Abstract

This study is an exploration of student meaning making in a non-traditional, high activity, hands-on grade 12 high school chemistry setting. The study focused on a sequence of three "open-entry" laboratory investigations (i.e., iodine clock reaction, pop-can cell and electroplating). These open-entry laboratory investigations were designed to be flexible and to take place in settings where students could make an impact. Students were responsible for devising their own problem and entry strategy, for making decisions about what reagents to use, what variables to manipulate, and how to proceed to develop the problem to a resolution acceptable to them and to the teacher.

To explore students' meaning making in open-entry laboratory settings, their interactions were video taped and samples of their written laboratory reports were collected from time to time. Students were also requested to write reflective notes on their experiences of each investigation. Some students were interviewed at the end of the course. This thesis consists of accounts and interpretations of what students did and said as they made meaning in these open-entry, hands-on laboratory investigations.

The research uses an enactivist perspective to explore the meanings emerging from the study. From an enactivist view, cognition is seen as perceptually guided action in which a knower brings forth a world of significance with others. Enactivism suggests that students do not only express their knowing in what they say or write but also in their actions with others within this learning community. The research revealed that meaning making in these circumstances was highly complex. It involved systematic trial and error at various levels within the multiple iterative feedback loops. Students' interactions in this setting were mediated by the culture of chemistry which is embodied in the practices

of the discipline. With students having to make decisions with every action, their meaning making was not only about physical phenomena studied. It was also about the whole being living in a community--involving their personal, interpersonal, social and cultural dimensions. Our teaching has to evolve to reflect an understanding of the complexity of these processes and allow students to make decisions about complex processes. It also needs to enable students recognize the constitutive role they play in knowledge making.

Preface

Outside the laboratory, hallways were quiet. Only occasionally might you see a person walking past. However, every eighty minutes a bell would ring and the hallways fill with teaming bodies of young men and women steadily moving from one place to another, carrying books and bags. It seemed they moved in groups or swarms, some talking, some laughing, others seemingly lingering around, to capture the last second of that social moment. It was usually difficult to move quickly through this crowd because the groups tended to occupy the entire width and length of the hallway. Soon after the second bell rang, all became quiet again, hallways deserted once more.

A friend dropped by the class once. She asked me later, "What grade was that? When I entered the lab it sounded like my third grade class. The room was full of life. Students milling about from one station to the other, hesitant looks, unfinished sentences uttered, arms reaching over to the group opposite, phrases offered, nods and smiles shared. What were they doing, they seemed busy?"

> *"We got it f--i--r--s--t! We got it f--i--r--s--t!" A student shouted, bragging to the other group. Arm stretched out as if to retrieve something from the other group, "We give you two minutes, two minutes!" was the reply. "Ha, look at that! Ours was way up there!" the other student retorted.*
>
> *"It is up to you what materials you want to use. Remember this is a work in progress," one adult said.*

"It could have been my grade five class," commented another observer.

"Oh, I thought it was grade nine," another teacher said.

"Did you notice how their questions changed with time?"

"What do you mean?"

"They asked more questions at the beginning and later their conversations were more statements, as if they gradually became masters of what they were doing."

"Yeah, I noticed that too. They tended to instruct more and more rather than ask many questions as time went on."

"Did you notice anything different about how the boys and the girls behaved? Did you see how that group of boys seemed to taunt the girls in the group opposite? They were so noisy too."

> *(Tap, tap, tap; tap, tap, tap) "Extreme conductivity, extreme conductivity!"*
>
> *"Did you see the white pen tapping? I felt like grabbing that pen away, what noise!"*

Imagining the students engaged in this activity, one might ask, what kind of learning was taking place? What were the students doing, saying, or writing? How far did they extend their knowing?

How could I, as a researcher capture this diversity, this vitality, this high energy? Can I fully communicate to someone who was not there just how complex, yet playful and sophisticated the processes the students employed were? How can I communicate this without losing the dynamism? How come most of my own classes when I was a student in high school were nothing like this?

When I started this research I had just completed a master's degree in organic chemistry. I chose to do a doctoral degree in science education because I am a teacher and I had a master's degree in science education. I had also learned from the two graduate programs that researching the natural sciences leaves one with very little time for family. Most of the work in natural science research can only be done in the laboratory, in the seminar halls, in special instrumentation laboratories, with specialists found in those rooms and also in the science library. I was married with four children whose growing up I did not want to miss. Rather than nourish a relationship with the lab, away from the family, as committing to chemistry required, I chose to build a relationship with each of my kids and my husband without giving up on my career. I needed the human relationship with my family to grow as a mother and wife. I chose education because it still allowed me to be the mother and wife I wanted to be. Education was practical given the commitments and needs of my family. I could take my work home with me and I could access many of the resources and materials I needed through the internet. Education allowed me to learn more about my relations not only with my family but with other people.

I had just completed a very exciting chapter in my life story that made chemistry and science in general become alive for me. I knew from reading, from the way science continues to grow and influence our every day living and from interacting with science researchers that science is not static. There was nothing more fascinating and educating to the whole being, and not just to the psyche, like living the experience of science coming alive. A new more fulfilling world of meaningful and embodied science emerged for me. I strongly felt I could do more with what I now know. In my undergraduate work in chemistry we never really did research in the sense of investigating an unknown phenomenon. Researching something that nobody had full understanding of had its own rewards. What difference could I make as a chemistry educator so that some students in the future may feel a sense of more fulfilment with their education or their research without necessarily having to go to university? What contribution could I make to show someone how exciting, sometimes frustrating and complex chemistry research was? As a high school student I was never really satisfied with the way science, especially chemistry was presented to me. It felt somewhat limiting. I could not explore questions that interested me. I wanted to be able to give some students a chance to ask their own questions, questions that they could explore in the school laboratory and become excited about living as a high school chemistry student. I, therefore, embarked on this journey.

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This study could not have emerged the way it did without the contributions of many people with whom I interacted. I owe a deep sense of appreciation and gratitude to all of them. The following people are only a few of them.

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Special thanks go to Dr. Heidi Kass for starting this research with me and for supporting me throughout the study.

I would also like to thank the principal, the teachers and students of the school in which this research was conducted. A good number of them, five years after the school visitations still remember me. Thank you for working with me. I learned a lot from our interactions.

I thank the occupants of rooms 948 and 229 past and present and other graduate students with whom I interacted in different ways. To my colleagues in EDSE 601, Cognition and Curriculum and all the professors we interacted with in that course, you always made the course interesting and challenging. This work will always remind me of the ways we are structurally coupled as you will always be part of this new world that exists for me.

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PART ONE

CHAPTER ONE

THE PROBLEM

> Meaning [*and understanding*] depends not only upon a sign and a referent but also upon an interpretant. (Bruner, 1990)

> Science is a dialogue between mankind and nature, the results of which have been unpredictable. At the beginning of the twentieth century, who would have dreamed of unstable particles, an expanding universe, self-organization, and dissipative structures? But what makes this dialogue possible? . . . Knowledge presupposes that the world affects us and our instruments, that there is an interaction between the knower and the known, and that this interaction creates a difference between the past and future. Becoming is the *sine qua non* of science, and indeed, of knowledge itself. (Prigogine, 1996, p. 153)

Introduction

School curricula, including chemistry curricula, are evolving towards increased complexity (see Figure 1). The purposes, goals, and accompanying processes involved in achieving the goals are multidimensional and interact in ways that generate new ways of knowing and being in our modern society. Not only does this curricular complexity involve the incorporation of historical, science-technology-society (STS), environmental, and nature of science into the set of student outcomes, but students are also expected to develop an understanding of this complex conceptual and theoretical knowledge as well as learn about science; that is, to learn about the nature of science, the methods of science, and the complex interactions between science, technology, society and the environment. In addition, students are expected to do science by engaging in

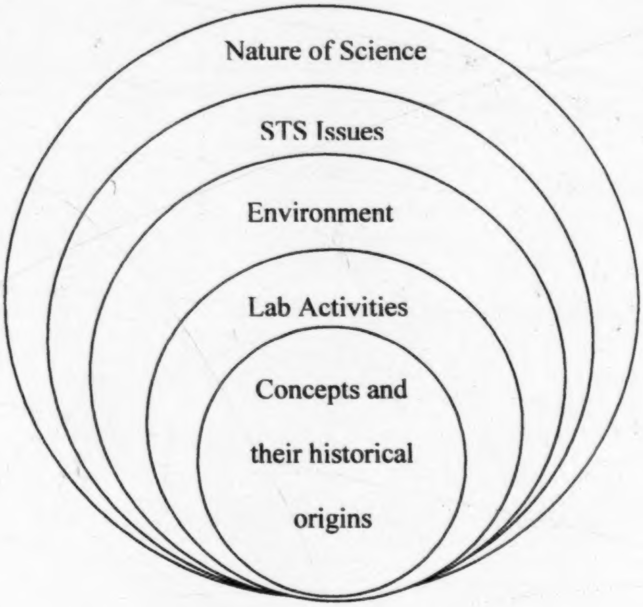

Figure 1. Complexity in chemistry curricula.

scientific inquiry and problem solving. The inclusion and interaction of these dimensions changes the epistemological complexity of the subject (Kass, 1991; Kass & Jenkins, 1982). As well, there is a corresponding change in pedagogic complexity and its impact on the ways that students engage in learning and meaning-making experiences (Kass, 1990, 1991; Kass & MacDonald, 1995; Kass, Pilane, Hong, & Jenkins, 1996; Martin, Kass, & Brouwer, 1990). Indeed, patterns of interaction among students have also become noticeably more complex. Hodson (1996) articulated this complexity when he noted that science education is seen as comprising three major elements: learning science (acquiring and developing conceptual and theoretical knowledge; learning about science (developing an understanding of the nature and methods of science and an awareness of the complex interactions among science, technology, society and environment; and doing science (engaging in and developing expertise scientific inquiry and problem solving. (p. 115)

Laboratory hands-on activities are also evolving to reflect some of this complexity. In curricula documents it is stipulated that laboratory hands-on activities should address the nature of science, science-technology-society, and environmental issues. In addition, laboratory hands-on activities are expected to help students develop conceptual understanding and an appreciation for science methods and epistemology. Contemporary high school laboratory programs have a variety of laboratory activities ranging from highly structured recipe types of activities to the less structured open-ended types of activities. The laboratory activities are designed to address a number of learning objectives, including manipulative skills, procedural skills, data-processing skills, and analytical skills; as well as to introduce, illustrate, and verify or support concepts taught in class. Many of the highly structured hands-on laboratory activities are used to verify concepts and theories. Few laboratory activities are designed to teach decision making, to falsify concepts, or to show weaknesses in concepts. Fewer still, are there laboratory activities in the school science program designed to nurture the habits of mind or predispositions, (e.g. perseverance, confidence and coping with uncertainty), necessary for scientific activity. Although the laboratory programs may include the more versatile and less structured activities, these activities are frequently not included by the teacher for students to do because these kinds of activities tend to be time consuming. They require that teachers and students spend more time preparing and carrying out the investigations. In addition, they require that more time be spent on one-on-one student-teacher interactions and evaluation. Teachers tend to omit the less structured activities because there are no well-defined teaching and evaluation strategies to help teachers. The International Baccalaureate (IB) program, which requires a significant component of less structured laboratory activity and a research project, provides an illustration of how these activities can work. The laboratory activities in the IB program are designed to teach higher level thinking skills and the nature of science and to engage students in doing investigative research in an interdisciplinary context so that they can develop an appreciation of the complex and dynamic nature of science. Students are expected to engage in a project in which they are involved in the planning phase, the performance phase, the recording and reporting phase, and the reflection phase. Students therefore engage in all of the developmental stages of the research. In the IB program teachers are expected to evaluate student performance in all phases (International Baccalaureate, 1996).

Understanding the complexity of the learning-teaching processes involved in the high school chemistry laboratory programs requires different ways of viewing and interpreting: a shift of focus from individual components of the program to more holistic and more integrative approaches. This includes an understanding where students' learning is analyzed and evaluated not only in terms of their finished product, the laboratory report, but also in terms of their evolution or progression towards understanding and using the processes of scientific inquiry themselves. Recent research studies have introduced complexity to the ways we describe, interpret, and make meaning of learners' engagements in these complex environments (Davis, Sumara, & Luce-Kapler, 2000; Gordon-Calvert, 1999; Kass & MacDonald, 1995, 1999; Kieren & Pirie, 1992; Roth, 1995, 1996, 1998, 2001a ; Roth & Bowen, 1995, Roth & Welzel, 2001;

Simmt, 2000). There is a co-emergent evolution in the dynamics, structure, and processes of science education that reflects this increasing complexity.

Although there are many dimensions of the chemistry curriculum that could provide a context for research, I am interested in students' meaning making in the laboratory setting. My interest stems from my experiences as a chemistry student and a high school chemistry teacher and also from the research I did for my master's degrees in science education and in chemistry. As a high school student I was always fascinated by the hands-on activities we did, of which there was a significant amount in the O Level Nuffield Chemistry syllabus. Much of this was new to me, but it kept me wondering what more I could learn in chemistry. For my graduate work in organic chemistry, a major component of the research involved isolating and identifying the structures of endophytic fungal metabolites. I also conducted a synthesis of one of these metabolites. To isolate and identify the structures of the metabolites, I did not use highly abstract theoretical concepts. I learned to do things with and in chemistry and contributed to the larger research of understanding how some coniferous trees in Eastern Canada were able to survive spruce budworm infestations. I learned to appreciate more the complex nature of chemistry by doing the research in the laboratory (Pilane, 1995).

Many contemporary high school chemistry curricula have a small laboratory component, and when students do laboratory work, it is mostly following recipe types of activities aimed at confirming concepts already taught in the classroom. Such laboratory work does not expose students to the complex nature of chemistry; indeed it may result in an overly simplistic view of chemistry. Seldom do students create or falsify concepts, authority, or processes with their laboratory work; rather, investigation problems are always presented to them that confirm concepts.

My concern with high school chemistry laboratory program is that students are exposed to one type of laboratory work. Although this approach has been used successfully to teach manipulative skills and to illustrate and confirm complex concepts, it does not expose students to understanding the nature of science and scientific inquiry. Students do not develop an appreciation of how diverse, dynamic, involving, complex, and personally meaningful chemistry can be. The laboratory activities, with which students are presented, although sometimes complicated and difficult, do not resemble scientific problem solving.□

For my research, I had to find hands-on laboratory investigations that were not a recipe type and that did not require understanding of abstract theoretical concepts that students could do and self-direct. My conjecture was that doing these kinds of investigations could be pedagogically useful to start addressing the complex curricula demands. Being able to describe, interpret, and explain how students and teachers interacted in activities, where we start "small and with uncertainty" (Roth, 1998, p. 1089) and was a little flexibility to introduce contexts of real-life scientific research would be useful to teachers who were contemplating using such activities in their classes.

Discussions and studies done on evaluation strategies in the IB program mentioned above might be used to develop a basis for evaluating open-entry investigations in the general Alberta high school chemistry program. The high school chemistry laboratory program outlined in the textbook includes a few open-ended technological problem-solving activities.

To understand what students learn and how they learn it, we need to understand the complexity inherent in the science curricula and also in the processes of making meaning. In this work, I borrow from some of the emerging theories of cognition and complexity to frame how we might think about student meaning making in the context of laboratory investigations.

My research is informed by emerging theories of cognition developed from new understandings of biology (Bateson, 1972, 1979; Maturana, 1988, 1991; Maturana & Varela, 1980; Varela, 1992; Varela, Thompson, & Rosch, 1991) and from recent work in chaos/complexity theory (Kellert, 1993) and systems theory (Capra, 1996; Prigogine, 1996; Prigogine & Stengers, 1984). These researchers view cognition as a complex dynamic phenomenon that cannot be understood through simplified reductionist approaches that separate knower from his or her environment, actions, and emotions. Cognition can, instead, be understood through holistic approaches that regard context and complexity as significant as the participants and the phenomena being studied. Cognition, according to these theories, is an irreversible process that allows the past to inform the future. What is learned cannot be unlearned, but it can be modified to facilitate further action. In these theories cognition is not just a mental phenomenon; it is a fully embodied process where our body --eyes, hands, ears, skin, tongue, and nose, for instance-- facilitates the process of "knowing or cognising." Although part of knowing is mental and can sometimes be verbally articulated, some aspect of knowing remains unarticulated and probably inarticulable in the body that smelled, touched, caressed, tasted, and felt the materials interacted with or investigated (Lakoff & Johnson, 1999; Neill, 1990). These new theories of cognition provide me with a means of observing students as complex multidimensional entities whose evolution is co-determined by their individual structure, history, and sociocultural environment. This has been labelled the *enactivist* view (Varela, Thompson, & Rosch, 1991). Understandings are enacted in the very process of living. In other words, students' actions and interactions in a setting are expressions of their knowing. In an enactive view of cognition, the student and all other participants are recognized as significant components of the context of meaning making and not external to it.

The purpose of my dissertation is to present accounts of students' interactions in open-entry laboratory investigations and to offer an interpretation of these interactions that explore the implications of open-entry laboratory activities and to offer insight into how students make meaning under these conditions. Specifically, my study explored 12th-grade students' engagements in open-entry chemistry investigations from multiple vantage points. I will discuss what students did; what they said; what they invited the researchers and the teachers to do; what they wrote about their action/thoughts; what the teachers, researcher, and other resource persons said; and what I understood from my interactions and engagement with them. To develop these understandings, the research problem presented below offered a reasonable starting point.

Research Problem

How do high school students make meaning in high-activity hands-on chemistry laboratory investigations that involve an increased amount of student self-direction? To find answers to this problem, my research explored the way or ways that student understandings developed in high school open-entry chemistry laboratory investigations that allowed for student decision making in the completion of the activity as well as interpreting the investigative procedures used. Several questions were raised to address this:

- How did students approach and complete open-entry laboratory investigations?
- How did students describe and explain their experience of open-entry investigations?
- What meanings did the students make from engaging open-entry investigations?

Conceptual Terms

In a traditional thesis one defines terms. Believing that this has a place and may help clarify some of the ideas presented, I offer a definition of terms used. Several expressions, words, and phrases used in this research have their meanings rooted in their (contextual) usage. However, there are some technical terms that arise and may need explication.

Account of: written descriptions and interpretations of experiences.

Co-emergence: an effect that can be observed when two or more systems unfold together, where the unfolding of one depends upon and also determines that of the other.

Enactivism: the theory of cognition that views cognition as a bringing forth of a world of significance with others.

Enact: the speech-action-thought processes that are part of cognising-in-a-setting.

Embodiment: bodily understanding or knowing that results from bodily interactions with phenomena.

Open-entry or variable-entry: coined by Simmt (1996) to describe activities or tasks that are open to multiple interpretations and therefore can be approached from different positions and have multiple solutions.

Structural coupling: a state of being that arises whenever there is a history of recurrent interactions between two or more systems that result in structural changes of the systems in such a way that the organisation and relationships (structural congruence) are maintained.

Terms used interchangeably in the dissertation include the following:

- learning and cognition
- understanding and meaning making
- laboratory investigations and laboratory activities

Specifying Context

This research was conducted in a large urban public high school. The chemistry curriculum used in this school is outlined in the Program of Studies for Chemistry 20-30 published by Alberta Education (1994). One major aim of this science curriculum is to increase the scientific literacy of all citizens by teaching science at all levels with an emphasis[1] and focus on the relationship of science, technology, and society. A challenge issued by Alberta Education's (1985) "Review of Secondary Programs" was to make everyone—curriculum and textbook developers, teachers, and students—responsible for the achievement of all goals of science education. This not only recognised students as active learners, but it also required that they be given the space to actively engage in this curricular transformation in the classroom. As stipulated in the program rationale and philosophy section of the *Chemistry 20-30 Program of Studies* (Alberta Education, 1994):

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[1] Curriculum emphasis as used in Alberta's science education is a conceptual tool developed by Roberts (1982) and used to cluster and organise science education goals. Its use has allowed curriculum developers and teachers to select and focus on specific goals and, in a sense, align them to specific science content and essential learning. A more detailed description of its use in Alberta's science curriculum will be provided later in this chapter under the section entitled "A Historical Context: The Alberta Advantage."

> The Chemistry 20-30 program places students at the centre. Students are active learners and will assume increased responsibility for their learning as they work through the program. A thorough study of chemistry is required to give students an understanding that encourages them to make appropriate applications of scientific concepts to their daily lives and prepares them for future studies in chemistry. Students are expected to participate actively in concepts and principles of chemistry that provide students with a more unified view of the sciences and a greater awareness of the connections among them. (p. 1)

The curriculum document outlines the science, technology, and society goals as well as the knowledge, skills, and attitudes expected. The major goals of the program are as follows:

- to develop in students an understanding of the interconnecting ideas and principles that transcend and unify the natural science disciplines
- to provide students with enhanced understanding of the scientific world view, inquiry, and enterprise
- to help students attain the level of scientific awareness essential for all citizens in a scientifically literate society
- to help students make informed decisions about further studies and careers in science
- to provide students with opportunities for acquiring knowledge, skills, and attitudes that contribute to personal development (pp. 1-2).

A separate document, written by the Alberta Education Curriculum Support Branch (1990), designed to help teachers integrate STS in their teaching described in more detail the structure and objectives of the science curriculum with this STS emphasis. Table 1 outlines the various curricula emphases incorporated.

Table 1

Components of STS Science Curriculum Emphasis

	Science	Technology	Society
1	Scientific knowledge	Technological knowledge	Societal knowledge
2	Scientific process skills	Technological skills	Societal skills
3	Scientific attitudes	Technological problem solving and design	Societal attitudes
4	Scientific problem solving	Technological attitudes	Societal decision making
5	Nature of science	Technology in science	Science and society
6		Technology in society	
7		Nature of technology	

The curriculum document makes a distinction between scientific problem solving, technological problem solving, and societal decision making based on the goals presented for each one. Whereas "scientific problem solving seeks explanation for natural phenomena, technological problem solving strives to develop practical devices or processes and societal decision making is concerned with what should be done about a particular issue" (Alberta Education, 1990, p. 14.)

In order to delimit the scope of the study, a decision was made that, given the program structure, there would be a focus on technological problem solving within the open-entry laboratory activities offered in this research. The data collected for this research involved students from (a) one regular Alberta Grade 12 high school chemistry (Chemistry 30) class that incorporated small-group laboratory hands-on student activity and (b) two Grade 12 IB high school chemistry (Chemistry 30 IB) classes that incorporated small-group laboratory hands-on student activity. Accounts in this dissertation describe, interpret, and explain students' interactions as they engaged in the open-entry investigations designed within this curricular structure.

This research used qualitative methods combining participant observation with interviews and class discussions to explore the meanings that laboratory activities had for students. Data were collected through the use of field notes, audiotaping and videotaping of students engaged in activities, interviews, and audiotaping of class discussions. I kept a research journal documenting periodically my own experiences and my interpretations of them and occasionally made copies of students' written laboratory reports documenting their explanation of various chemical systems. Students also wrote reflective notes about their experiences in these investigations.

Although the study was focused on student meaning making, it is clear that as an observer I had to make inferences about that meaning making based on student talk, actions, and writing. Some students were able to communicate their ideas; the more they said and did within the laboratory activities, the more data I had to work with.

A Historical Context

The Alberta high school science curricular reforms have been influenced by the global science curricula reform movements. A brief historical description of the evolution of high school science education internationally is presented here to set the context of the curricular decisions that were made for the research. The past 50 to 60 years have witnessed many reforms in science education. Curricular reforms initiated in the late 1950s in the West brought issues of science and science education to the public eye. The coincidental simultaneous launching of the Russian Sputnik tended to accelerate and magnify the urgency of these reforms because such a development seemed to imply that science and technology in the West was lagging behind (Brock, 1992). The reforms were aimed at improving science education, which was tied in with the existing views of economic progress, industrialization, and development (Fensham, 1984; Maddock, 1981; Yager, 1982). Also linked to this was a concern by colleges and universities that the courses they offered were outdated and too factual. This concern widened in scope to include the science background knowledge that students brought from school. It was felt, in chemistry, for instance, that the discipline had grown and continued to grow in diverse ways that resulted in high school graduates entering the institutions with widely disparate backgrounds that made teaching common courses almost impossible. Knowledge in chemistry had developed sufficient internal consistency around which it could logically be articulated[2] and taught (Brock, 1992; Strong & Wilson, 1960). It should be noted that in the United States, apart from the indirect influence of Dewey's and Bruner's thinking on education at the time, perhaps brought to bear on these curricula reforms by the teachers involved in these projects, the curricular reforms were predominantly steered by specialists in the science disciplines.

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[2] The Reed College conference of June 1957 set in motion the beginning of the reform for the Chemical Bond Approach project. This was followed up by the Wesleyan conference in 1958 with preliminary school trials of some of the materials in 1958-1959 and a subsequent writing conference in June 1959 held at the Reed College.

Although science and science education, guided by the psychology and goals of education of the time, had been elitist, catering to about 20% of the student populations from whom future scientists would come (Fensham, 1984), the advent of the Sputnik seemed to make it even more elitist. In school chemistry curricula, for instance, there were drastic shifts from descriptive and technological emphases to more conceptual and theoretical emphases (Fensham, 1984, 1985; Hofstein, 1988). School curriculum reforms, especially those with a significant American influence, brought about developments that removed the practical application and technology emphasis from the curricula to focus on theoretical and abstract conceptual content, considered to be tailor-made for university undergraduate degrees; e.g., CBA, CHEM Study,[3] PSSC, and BSCS (Fensham, 1983, 1984; Maddock, 1981). The teaching of theory was considered to be powerful enough to compensate for the removal of the descriptive, technological, and, perhaps, fully embodied knowledge because knowledge of that theory would supposedly empower students to generate more powerful ideas or theory and to advance science and technology. As Hofstein said in his invited lecture to the IUPAC symposium in Sofia, Bulgaria in 1987, "It was commonly accepted that school science should be presented in a way it is known to (*and known by*) scientists. In fact it was postulated that if science were organised and presented in that way it would be inherently interesting to all students" (p. 40).

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[3] W. H. Brock (1992) reported that CHEM Study was not advised by educationists and psychologists. Unlike CBA, it was prepared to simplify or ignore material for the sake of better understanding.

Alongside these shifts was a gradual increase in the school population. By the 1980s the demand for school science had risen from about 20% of the secondary school population to more than 60% (Fensham, 1984). The relative uniformity in ability and aptitude witnessed previously with a few elite students was replaced by a wide range of student ability as the student population became more heterogeneous. Consequently, the elitist science curricula could not address the scientific literacy needs of the majority. The demand for scientists in the various fields and industries continued to rise, but the supply of qualified personnel was dwindling, especially in Europe and North America.

The ensuing science education and science education research, in an effort to raise enrolments and "achievements" in science and provide "science for all," was strongly influenced by theories of learning and cognition (Fensham, 1985; Science Council of Canada, 1984). Bruner's influence in North American education and in the development of the new curricula of the 1960s was reflected, for instance, in the CBA materials (Brock, 1992). Although Piaget's studies with children in Europe were published as early as the 1920s (Piaget, 1971), their greatest impact in the school system was not felt until the 1970s. Piaget and Ausubel emerged as two major influences in debunking the thinking that students were "empty vessels" or receptacles and teachers were transmitters of knowledge. This marked the birth of the constructivist movement in school science. How much this thinking has actually transformed classroom teaching and learning is debatable. However, the past three decades have witnessed science educational research focussing on the application and perceived outcomes of these ideas in the classroom.

Different interpretations of Piaget's (1970) *Genetic Epistemology* emerged and were reflected in the research that followed. Part of that research focussed predominantly on developmental stages and "cognitive demand" in science education (Flavell, 1977; Lawson, 1985; Lovell, 1980; Niaz, 1986; Shayer & Adey, 1981), partly on intellectual (conceptual) development and advanced organisers (Eylon, Ben-Zvi, & Silberstein, 1986; Griffiths, Kass, & Cornish, 1983; Novak & Gowin, 1984), and partly on students' frameworks, conceptions, and preconceptions (Andersson, 1986; Driver, 1983; Driver & Easley, 1978; Gilbert & Osborne, 1980; Nussbaum, 1985). The perceived challenge for most of the research at the time was to try to develop a "science of science teaching" and to accelerate learning (cognition).

Because the sciences have historically developed into the present-day disciplines and fields by focussing on, manipulating, and explaining different areas of the physical world, it seemed reasonable that an attempt to develop a science of science teaching would require a similar approach to cognition, learning, and teaching. Using the tools and models adopted from the understanding of science, learning was perceived to be hierarchical and linear in structure (Gabel & Sherwood, 1980; Herron, 1985; Howe & Durr, 1982; Shayer & Adey, 1981). From this view, instruction could be structured to fit this learning in which whole courses could be developed and organized to show the logic of the discipline.

The Alberta Advantage

Science curricula have evolved over the years towards increased complexity as we developed more understanding of ourselves and our environment and with the changing needs of our society. This evolution has left practitioners with little guidance as to what to do and how to handle this complexity in teaching. Curricula structures that address this complexity are needed. In Alberta, recognition of this increasing level of curricula complexity is gradually being addressed, not in a revolutionary manner but in an evolutionary way. Many of the curricula changes in high school science in Alberta originated in the 1970s from classroom teachers who at one time also became graduate students seeking to understand this complexity for themselves and their students. The research studies conducted by these teachers are documented in several master's and PhD dissertations and publications thereof (Jenkins, 1981, 1987, 1996; Lantz, 1984; Roberts, 1982). These studies culminated in the current curricula structure that has also been used in the development of some of the high school textbooks (textbooks (Jenkins, van Kessel, Tompkins, Falk, Lantz, Dzwiniel, 1993, 1996). The structure of these science curricula, especially the high school chemistry curriculum, recognizes that

- there are many different science education goals
- some of these goals sometimes conflict
- science teaching cannot achieve all goals at once.

A three-dimensional (cubic) model was developed around which the different educational goals were organized. In one dimension essential learning goals were defined, and these were grouped into knowledge, attitudes, and skills. Another dimension clustered under curriculum emphasis identified the science, technology, and society goals; and a third dimension identified science topics or concepts to be taught at various levels. This model allowed these curriculum-developer teachers to define more specifically what goals could be emphasised when teaching the different chemistry units. An understanding of this structure can enable teachers to begin to handle some of the complexity of high school science in the classroom teaching and learning. This model offers a starting point to begin to systematically address this complexity.

The Research Significance and Context

In the past three decades constructivist research in science education has focused on creating innovative instructional strategies that would enhance conceptual change and meta-cognition. The research on students' alternative conceptions in science has focused on concepts that include heat, electromagnetism, particulate nature of matter, sound and waves, and gravity (Driver, Asoko, Leach, Mortimer, & Scott, 1994; Fensham, Gunstone & White, 1994; Gabel, 1994; Levinson, 1994).

In addition to students' conceptions, chemical education research has also focussed on problem solving. Two chemical education research reviews conducted in the past decade by Gabel and Bunce (1994) and Herron (1990) reflected this focus in the studies cited. Although problem solving in chemistry, in its broad sense, has a potential for the use of diverse strategies and can cover and integrate a wide range of content areas, its historical influence by mathematical problem solving and physics has tended to restrict it to strategies and content areas that have a strong mathematical emphasis and that could be evaluated by using paper-and-pencil tasks.

Research that viewed knowing or knowledge as a complex process and incorporates holistic, ecological, or evolutionary ideas to understanding students' meaning-making processes has emerged within the past 10 to 15 years. The research has focused primarily on high school physics (MacDonald & Kass 1995, 1997; Roth & Lucas, 1997), biology (Rymer, 1997), and mathematics (Davis, 1995; Kieren, Simmt, Gordon-Calvert, & Reid, 1996).

Few studies have looked at high school chemistry students' learning from this perspective (Ebenezeer, 1996). Many research studies conducted in different countries indicated that students have fragmentary understanding of concepts and are often unsuccessful in problem solving that requires application of the conceptual knowledge (Bunce, Gabel, & Samuel 1991; Fensham 1984; Gabel 1994; Lythcott 1990). The study of high school chemistry learning and teaching is made more complex by the fact that this chemistry not only deals with situations that are abstracted from the students' natural everyday experiences, but also requires learners to imagine and infer properties and behaviours of things they cannot see or manipulate. Everything in a chemistry class is a re-creation or reconstruction that is very tightly controlled. For most introductory learning, chemistry's appeal is based on its magic and therefore is not easily explained or understood.[4]

In my experience in teaching chemistry at high school and at university, students enjoyed hands-on activities. The activities provided them with something to which they could relate mentally, physically, and even emotionally. The activities were their creation in a sense, and they could describe what they did, although they could not always explain it. They were doing something in or with chemistry in school. Using constructivist ideas, I could tell that students had difficulty explaining chemical events partly because of the nature of scientific explanations, which often were different from their everyday explanations of their experiences. The criteria of chemical explanations required language inferences, extrapolations, and models with which they were not familiar.

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[4] For some students the novelty of the phenomenon and the spectacular sensory effect it had was perhaps a satisfying end in itself. The experience did not necessarily need any explanation. In my case, however, some connection had been made with my home experience, which I could now use chemistry to describe and explain. Maybe if I listened and learned more I could describe and explain more of my world with chemistry; hence my fascination with explanations given.

Although ideas from constructivist research efforts have transformed educators' views of learning/teaching, research seems to suggest that, globally, the desired results, (raising of achievements and enrolment in chemistry (in science) and transfer of scientific knowledge to practical novel settings) are still unrealized. Exceptions exist in Alberta's senior high schools, where high participation rates are reported.[5] The problem is made more complex by the multiple and sometimes conflicting demands that the new curricula make on students and teachers. The introduction of the nature of science, the history of science, and science-technology-society and environmental issues into science curricula, coupled with the teachers' desire to teach towards concept mastery, raises the need to redefine science education, to rethink our theories of knowing and learning, and to change our pedagogical approaches to school (chemistry) science (Kass, 1991; Kass, Hong, Jenkins, & Pilane 1996).

> Chemistry is a much broader subject than the one that is currently being taught in schools and universities, majoring as it does on 'pure' chemistry and 'rational' theory. I believe that those of us who are responsible for the teaching of chemistry should try to enlarge the conception of the subject, and to deal with aspects of it that we are presently tending to neglect. (Nelson, 1983, p. 125)

Despite the wide acceptance of the view that students are active learners and create their own meaning espoused by the constructivist cognitive model in science education and science education research, little has changed in the chemistry classroom.

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[5] Interviews with high school chemistry teachers in Alberta revealed that student participation rates in chemistry were quite high, even higher than the national average. At the school where I did the research, it was not uncommon to find more than 60% of the school population taking chemistry.

Students have few opportunities or occasions to play with and explore chemical phenomena to enable them to make sense of the phenomena themselves. The emphasis on the evaluation of end products leads to instruction that tends to view knowing, learning, or meaning making in terms of inputs and outputs. Teachers transmit knowledge to the students. The effectiveness of the transmission model is often limited to rote learning. Working with the constructivist model within a structure that emphasizes end products tends to limit the learning possibilities. Enactivism, on the other hand, builds on these constructivist ideas and proposes a shift of focus from end products to processes as well. Enactivism allows us to examine, explore, and expand our notions of knowing and understanding to include processes and not just products of cognition. Knowing in the latter sense involves the whole being, the history, and the context of knowledge creation. This would enable us to capture the complexity and sophistication of students' understandings and meaning-making processes. Howe (1996) challenged us:

> We have now had much experience with these ideas and practices and found that, as useful as they are, they do not explain all we see or serve as guides to all we would like to do. It is time to broaden our vision of how children learn science. (p. 49)

In an attempt to broaden our vision of how students learn science, this study is aimed at developing an understanding of learning/teaching by identifying and interpreting the processes of meaning-making that students use and consider important in open investigative environments in high school chemistry. What are some of the students' perceived epistemological positions? Belenky, Clinchy, Goldberger, and Tarule (1986) talked of received knowledge in which the students perceive themselves not as creators of knowledge, but more as receivers and users of knowledge—a listening to the voices of others with authority. Often in science teaching students are not taught about some of the philosophical (or epistemological) ideas that have influenced the evolution of the subject. If at all some of these ideas are mentioned, they are not integrated into students laboratory activities for students to develop an experiential knowing of the influence they have had in the development of the subject. Karl Popper's falsification ideas and how they may be incorporated in our chemistry teaching and in the laboratory programs, for instance is one example.

For many students, chemistry is learned mainly through listening, repeating after the teacher, and working on problems and laboratory investigations that are rigidly controlled by the chemistry teacher. Students work hard to second-guess the teacher; they do not necessarily understand for themselves what chemistry is all about. Few recognise that they already have some intuitive or embodied knowing about some of the phenomena they study and that they bring this knowing into their learning of chemistry. Those who recognise it tend to disregard their intuitive knowing and prefer to repeat what the teacher says. Quite often students would judge their actions as guessing or luck.

In teaching science at all levels, not only do we need to take students' knowledge into account, but we must also create spaces and opportunities for students to become active learners so that they can personally make meaning of their learning. After all, no matter how hard they try, teachers cannot learn for their students. The incorporation of problem-solving science activities into the program would help facilitate students' meaningful learning. The recent resurgence of interest in inquiry-based learning in international science curricula discourses (Hodson, 1996; Jenkins, 1995; National Research Council, 1996, 2000; Roth, 1995) makes Alberta one of the leaders in the field. Given the demands placed on teachers from teaching problem solving, studies showing examples or describing how chemistry problem-solving activities can be approached have the potential to support teachers who are contemplating teaching inquiry in science in their classrooms. This study is one example.

Organization of the Dissertation

This dissertation has three parts. Part one gives the background to the research and consists of the first four chapters. The second part describes the research and has four chapters as well. The third and final part is an overview of what the students and I have learned through the research and the implications that it has for science education, for school science, and for school chemistry teaching and learning.

In Chapter One I describe the research problem. In Chapter Two I discuss the theoretical perspectives that have helped shape this research. In it I discuss theories of cognition and the different ideas from enactivism that I have used to interpret my research. Chapter Three is a discussion of the research on chemistry education: what has been done, what we have learned from it, and what needs to be done. Chapter Four gives a more in-depth look at the status of high school chemistry, describing its culture as it relates to pedagogical practices and how the culture has or has not changed. It also points to possibilities in the evolution of this culture.

Chapter Five tells the story of my research journey, how I designed the research and what processes I used to arrive at this stage: gaining access and collecting, analysing, and interpreting data. Chapters Six, Seven, and Eight tell the story of the students' interactions with chemistry. In these chapters I try to describe the processes that students used to develop meaning for themselves; I used as much as possible students' actions, utterances, and my interpretation of our interactions. In Chapter Six I give an account of students' interaction with the iodine clock investigation and what they have learned. In Chapter Seven the accounts are about students' engagement with the pop can cell activity. Chapter Eight describes students' interactions with the electroplating activity.

Chapter Nine presents some of the conversations I had with students after the course about their learning and the kinds of meanings that emerged for them from the open-entry investigations. I also present here some of the coherences that emerged for me about the processes that students used in making meaning. Although enactivist ideas have been used throughout the research, in Chapters Ten, Eleven, and Twelve I elaborate on how these ideas have informed the study. I also discuss implications that the research has for chemistry teachers, educators, and curriculum developers.

CHAPTER TWO

FROM CONSTRUCTIVISM TO ENACTIVISM: A THEORETICAL POSITIONING

Traditionally research into students' understanding of chemistry has focused on isolating what was identified as the cognising agent (the student), presenting to the student piece-meal, highly structured sets of instruction, administering a variety of tests (usually paper and pencil) and interviews and looking at the end product (student performance) to determine whether the student understood or not. Little attention was paid to the processes students used to reach the end. Attempts to develop a "science of science teaching" based on the different interpretations of Piaget's genetic epistemology have resulted in trying to identify, control and manipulate the "components" of learning (cognition) including problem-solving, memory, conceptualizing, imagining, creating, classifying, symbolizing, generating plans, fantasizing, and thinking (Flavell, 1977). In the research literature (Resnick, 1987; Niaz, 1995, 1996, Shayer & Adey, 1981) some of these components have been translated into research variables like conceptual demand, memory demand, learning environment, and attitude. Using these variables separately, simplified hierarchical models have been developed to illustrate how these factors could be controlled or manipulated (Niaz, 1995,1996; Shayer & Adey, 1981) to match the perceived student capability (Adey, 1989; Finster, 1989). However, these have had limited success in capturing the dynamic nature of the processes of understanding science (Klapper, 1995; Nussbaum, & Novick 1982).

There are several important questions to ask regarding the nature of understanding, meaning making and cognising. These are: What is the nature of cognition? Is it pure abstract thought or is it intimately connected to our bodily structures? Are our understandings and descriptions of the world, reflections of an independent reality or constructions of ourselves, the observer? Is there an independent reality at all? In other words, are the processes of meaning making, and cognising solely mental acts performed by an individual which would imply that we can isolate our research subject and ignore the environment and context that the subject exists in? Or are these processes more than just mental acts, co-dependent on the context and history of interactions? My understanding of cognition as an evolving process that is more than just a mental act compelled me to seek a different approach to exploring students' meaning making in high school chemistry.

Knowing/Cognition

Every time we try to define or describe what knowing is we fall short. We become dizzy, for the only way we can understand knowing is through our own knowing. Mostly we are so embedded in the experience of living that we are not aware of or forget the processes that lead us to this knowing. The dizzying effect emerges from the circularity of trying to use the "instrument of analysis to analyse the instrument of analysis" (Maturana and Varela 1987, p. 24). This does not, however, suggest that we give up because every little attempt changes our understanding and opens different avenues for exploring and getting to understand more this complex phenomenon.

The question of how we come to know has received much attention in western philosophical, educational and psychological thought since it is fundamental to the conceptualization of education and learning. Is knowing an epistemological question or an ontological question? Much debate has gone on about the mind-body, theory-action dichotomy as it relates to how our being in the world affects our knowing of the world (ontology and epistemology). Many theories including Skinner's behaviourism, connectionism, representationism, information processing and constructivism have been proposed in an attempt to address the question of how we come to know. Since Descartes, debates about the cognising subject or unit have also received much attention (von Glasersfeld, 1995; Piaget, 1970; Vygotsky, 1978). The subject of my research does not debate these theories but recognises that they all have contributed towards our conceptualisation of cognition, more specifically to human cognition. For instance, they have pointed out some of the traits of human cognition or inadvertently shown us, through their explorations, what human cognition traits are not (as in artificial intelligence and information processing). The contributions of these earlier discourses have not only transformed us and our conceptions of cognition but also the nature of cognition itself. We are therefore able to discuss and expand our understanding of cognition.

Constructivism

> Nearly three decades ago the acceptance of Piagetian conception of cognitive development liberated science education from the deadly influence of behaviourism, the dominant educational theory of that time. "Hands-on", discovery and finally constructivism became the watchwords and guide for curriculum, instruction and research related to science education. (Howe, 1996, p. 49)

How can constructivism be understood? Is it a psychological, a pedagogical, an epistemological theoretical construct? Constructivism like all complex constructs or concepts born out of languaging, communication and communication about communication, a process that Maturana and Varela (1992) describe as "coordination of coordinations of consensual actions" is susceptible to multiple interpretations. The main idea that forms the backbone of constructivism recognises that students construct meanings for themselves about the world (Driver & Oldham, 1986). Although there are differences in interpretation within the constructivist community, most of the research studies in science education have tended to approach it from the "softer" social constructivist perspective. From this perspective, there is a correct scientific interpretation and explanation of phenomena which students should be taught, a Kuhnian scientific paradigm (Kuhn, 1970). Rallying behind this perspective, in which pedagogical implications are embedded is the "student's conception" or "conceptual change" movement. Radical constructivism on the other hand rejects the representationist ideas of a "true" reality or a world separate from the knower. Although the nature of constructivism has not been debated much in science education, the latter perspective of constructivism has found some favour in the mathematics community (Cobb, 1994; Davis, 1996; Kieren & Simmt, 1999). The question is how have these ideas influenced science education and science education research?

Review articles on science education research cite a large number of research studies focusing on students' conceptions or children's science (Driver and Easley 1978; Driver and Erickson 1983; Gabel 1994; Herron 1990). The entire conceptual change movement including projects of the Children's Learning in Science (CLIS, 1987) and Cognitive Acceleration through Science Education (CASE: Adey, 1989) programs in the UK, the Project for Enhancing Effective Learning (PEEL: Baird and Mitchell, 1986) program in Australia, the Alternative Conceptions Movement (ACM) of North America are all offshoots of constructivist ideas. These research efforts have built an important global research community, developed a repertoire of research approaches and a shared vocabulary necessary for learning and exchange of ideas. They have also informed the education community about the wide range of possible results arising from instruction (Fensham, 1984). Despite the success stories reported from some of these programs, there are still many students who fall through the cracks as enrolments and interest in school science globally continue on a downward trend. As a result some researchers and educators are starting to look for new ideas (Ebenezer, 1996; Fensham, Gunstone & White, 1994; MacDonald & Kass, 1998, 1999). Ebenezer's (1995) study reflects some of the difficulties of translating constructivist research ideas into pedagogical practice. For instance, the accumulated body of information that we think should be passed on to students is large and results in rapid transmission giving little time for the students to linger, play with and create meaning for themselves. This makes it difficult for teachers and students to have time to reflect on their own teaching and learning engagements or on new ideas to learning. Recognition of the need for a playful lingering on ideas and concepts by students is implicit in Fensham *et al* (1994) and Ebenezer and Erickson's (1996) discourse on evolutionary conceptual change or dispersion in chemistry in place of the more confrontational approaches that may intimidate students.

Phillips (1995), for instance, shows the different perspectives that could be used to understand constructivist discourse. He argues that knowledge-making is more complex than the apparent dichotomies presented in constructivist discourse between individual and social knowledge-making, active versus spectative learning and emergent versus representationist knowing. Time is ripe for new ideas that can capture that level of complexity.

Although the non-representationist ideas of radical constructivism (von Glasersfeld 1995) may extend constructivist thinking by introducing the notion of viability and opening up possibilities for expanding outcome spaces in meaning making, it does not explain how our action and body are implicated in cognition and meaning making. It still portrays understanding as a mental (psychological) activity only. It provides no language to start discoursing about the fluidity and influence of the environment, desires and intentionality of the student and the teacher. It also fails to recognise and address the question of ethics in science, in education and all other human endeavours.

The epistemic stance of "enactivism" not only connects the biological theories of evolution and the quantum physicist's notion of chaos, relativity, complexity to the educators' notions of teaching and learning, it provides a way of articulating and inquiring into the once "inarticulable" messy nature of these processes. It also tends to eliminate the separation of mind and body or theory and action. Seen in totality it is not only about dynamism of the teaching and learning processes or the minute detail of interactions, it is as well a conceptual framework at the macroscopic level of relations in everyday life in school and out of school. It not only questions the “what” and the “how” but also the why, when, where and what if - the moral, philosophical and ethical nature of human activity or knowing. For me as an educator, it provides a window through which I can inquire into the "black-box" of learning-teaching.

Enactivism: A Bringing Forth of a World of Significance

Enactivism offers us a broader and more encompassing theory of human cognition as it is understood today. Maturana and Varela (1987) describe cognition as "the effective action by a living being in its environment" (p.29), an interaction that sustains the co-existence of the organism and its environment. According to the enactivist school, knowing is doing and doing is knowing. In the act of living, knowing happens to us and we come to understand ourselves and our environment. It is a continuous irreversible process that leads to continued living and knowing. Knowing is a process of becoming and therefore is not separate from learning and living.

According to enactivist thinking, human knowing/learning, like all complex processes, is characterised by perpetual novelty arising from the continuous creation and recreation of mind-body-environment. From this perspective we can conclude that knowing/learning is dependent on teaching but it cannot be determined by it. Enactivism suggests that teaching cannot predict students' meaning making (what is learned) because teaching does not cause knowing/learning. Teaching offers perturbations which students may interact with in their meaning making. It is more of an invitation to shift attention, to influence perception, to focus and interact with phenomena. Our ability to notice and mark novelty encapsulates our bringing forth a world of significance. Experience co-emerges with the evolving mind-body-environment readiness as our world of significance evolves. Teaching and learning demand that all participants in education be able to capture the novelty of their engagements and bring forth a world of significance for all engaged. From the perspective of the knower, whatever is not known is non-existent, what is not recognised does not have significance or meaning for the particular individual. Therefore in learning to recognise things, ideas, or concepts we make demarcations and create distinctions in the process of making meaning for ourselves thus bringing forth a world of significance. Our ability to know and to enact that knowing through living depends not only on our mental capacity, but on our biology (structure), our history and on our environment. These ideas of knowing and learning are the backbone of enactivism. In the next section I will discuss some of the themes of enactivism that emerge with this new understanding of knowing and cognition including embodiment, co-emergence, structural coupling, context and self-referencing that help me articulate my understanding of the processes of learning chemistry.

Embodiment in Cognition (Knowing)

> By elucidating the way our bodily processes participate in our perceptions we will throw light on the bodily roots of all [*cognition/learning*] thought, including [*the human being's*] man's highest creative powers... It is not by looking at things, but by dwelling in them, that we understand their joint meaning (Polanyi, 1966, pp. 15-18).

The processes of learning or meaning-making in a chemistry class are non-linear and involve embodied meaning-making or knowing. The meaning(s) emerges not only from the mental interactions with concepts or theory of phenomena being studied, but also from the bodily interactions and experiences with phenomena in a setting (Johnson, 1987; Maturana & Varela, 1992; Varela *et al.,* 1991). Our body is our only means of contact with a world external to us; therefore our perception of that world depends on the interactions of the body and the world (Johnson, 1987; Polanyi, 1966). Although our perception is not able to focus on everything we interact with to bring it to our consciousness, some of the knowing arising from that interaction remains unconscious and unarticulated in the body--what we often call intuition. Mingers (1995) described in a simplified way the process of embodiment as an act of the body, including the nervous system, acting on the bodily states that are triggered by an external perturbation such as heat resulting in the body knowing how to act effectively in the presence of heat to maintain the necessary relations that make an organism an organism.

> The nervous system allows the relations that occur at the sensory surface to be embodied in a particular pattern of nervous activity. With the growth of interneurons, this pattern no longer has a direct effect on the motor surface but constitutes a perturbation for the internal nervous system itself. The state of relative nervous activity becomes itself an object of interaction for the nervous system, leading to further activity. This is the basis for a further expansion of the cognitive domain, a domain of interaction with its own internal states as if they were independent entities. This is the beginning of what we term abstract thought. (p. 73)

The ways in which we each and/or collectively experience natural phenomena are framed by the ways our mind-body unfold in this co-emergence. Johnson (1987) and Lakoff and Johnson (1980, 1999) argue that even the metaphors we use to articulate our understanding originate from our bodily experiences and our being in the world. The whole body therefore is part of the context or setting of meaning making. How does a student know that a reaction in solution, for instance, is exothermic or endothermic if there is no bodily contact with the reaction vessel? The student can either directly touch the reaction vessel or indirectly touch the reaction mixture by using a thermometer. With Polanyi (1966) I would argue that even in the use of a thermometer, the thermometer becomes an extension of our body as we pour our senses into (or dwell in) the thermometer and allow it to connect to our sensory receptors. Our interaction with the reaction mixture through the thermometer allows us to make our history of interaction with the thermometer a guiding stick or an object of interaction for the nervous system leading us to our conclusion about phenomena being studied. The reading only has significance if we can interpret it by connecting it to our bodily experience of temperature.

> Embodiment is double stranded [*or even triple stranded as described by Kieren, 1996*]. "It encompasses both the body as a lived, experiential structure, and the body as the context or milieu of cognitive mechanisms [*and body as the body of accumulated information*]." (Varela *et al.*, 1991, p. xvi)

Describing embodiment this way does not suggest that there is a clear distinction where one can isolate one strand from the other. However, I will try to give examples where I think the two strands may be seen. Life is clearly a chemical or electrochemical phenomenon but our level of consciousness to the chemistry of life almost never surfaces in everyday interactions. It is in most cases subsumed in the biology of the body and becomes evident in instances where there is need for intervention. Our being in and with the world can be understood as a chemical phenomenon. We live because our bodies are complexes of actions, circulations, chemical exchanges, and electrical charges in constant variation. This moving flux of changing processes in the body is the dynamic magic of our existence and of our experiences.

Our body knows our chemistry and that of our environment since the two have co-emerged through evolution in a natural drift determined by adequate conduct or viability of their interactions and structural change. Therefore our body interacts with our environment (as a cognising unit) in such a way that the two can co-exist. When there is a perturbation from the environment e.g. lack of oxygen, substance abuse, infection or even a simple act of ingesting food, our structure, our chemistry changes, interacts with the environment, for example, by producing enzymes and other bodily chemicals which help in the breakdown of food allowing the body to select what it needs and passing on what it does not need. These processes, in turn, change the environment such that our internal organisation and our relationship with the environment remain invariant and the two continue to co-exist. This interaction, however, serves to expand the individual's cognitive domain (the body has been structurally changed or shaped as it learned how to deal with changes).

To follow the case of infections a little further, for instance, acquired immunity, as we understand it today, is a clear example of structural change that expands the body's cognitive domain such that any future "invasion" by the pathogen is easily recognized and dealt with, often without symptoms of infection surfacing. By being aware of the chemical balance or imbalance the body learns or make sense of its environment, and embodies the knowing. The body learns and is able to remember the bodystates including the neuronal networks and the structural changes or processes that allowed it to deal with the infection. That is the basis of what, in everyday language, we call immunity.

In a teaching-learning situation, chemical knowing of properties and processes is embodied. Some of that embodied knowing is reflected in what we normally refer to as intuition. Intuition evolves with experience and at times with subconscious awareness, where the body tacitly knows and has marked features of the experience without it coming to our focal attention. Through experience, both the teacher and learner learn how to interact adequately within the given environment. How and when does a teacher know when to use a small scale demonstration experiment in class rather than a full-blown class laboratory exercise? Through experience the teacher embodies and enacts that pedagogical content knowing. Although it is often difficult to describe how and when that knowing emerges or to prescribe when to use it, by being immersed for an extended period in interactions that require use of such knowing, the body knows how to act in the moment to address the situation. When do students know, for instance, when to stop heating a reaction vessel or when to stop adding a reagent or when the reaction has gone to completion? Through hands-on experiences they all learn to embody this knowing. Learning chemistry involves learning how to be and how to do things.

Context or Environment

> The word context is widely and ambiguously used in science education literature to mean a variety of things such as the classroom, the learning environment, relevance and a backdrop on which to base an activity … The term context refers to more than the social milieu in which activities are embedded. (Rodrigues & Bell, 1995, p. 798)

Enactive understandings of cognition regard context as an integral part of the process of meaning making. If context is part of meaning making how can we describe it in ways that would help us make sense of the contributions it makes towards this meaning making?

I have focused on bodily origins of knowing when talking about embodiment, however, this does not mean that knowing emerges exclusively from the body. Knowing is also contextual. It co-emerges with our context or environment in a process that involves body acting in a setting (or in its environment). What do I mean by environment? In everyday use, the word environment means everything external to us. It is important to note that in our existence we do not interact with or experience everything external to us. We define our environment in terms of what we interact with outside our body. Environments are not pre-specified they are relational (Lewontin, 1991). Organisms determine or define their environment or their context. In his Massey lectures (1991) entitled *Biology as Ideology, the doctrine of DNA*, Lewontin argues that

> There is no "environment" in some independent abstract sense. Just as there is no organism without an environment, there is no environment without an organism. Organisms do not experience environments. They create them. They create their own environments out of bits and pieces of the physical and biological world and they do so by their own activities. ... And we can know what the environment of an organism is only by consulting the organism. (pp. 83-84)

The recent discovery of extremophiles, bacteria and other organisms that exist in environments that were previously considered (by scientists) too harsh to support any life (Cavicchioli & Thomas, 2000) attests to the merits of this view of cognition and life. Our definitions and conceptions of life, for a long time blinded us to the possibility of their existence. In our minds and in our world, these organisms were non-existent. We based our conceptions of life and world on our immediate experiences which reflected how far we had reached in our evolution. By extending our bodily experiences through our tools we literally brought forth, for ourselves, a whole new world. Through interactions, languaging and sharing of experiences, a different thinking in biology emerged that allowed us to bring forth this new world of significance. With this thinking, we are now able to make some sense of this new world and to navigate our way, understanding the relationships that define who we are and what our roles in that world are. The context within which we live, which we ourselves have created and are part of, together with our own actions have created opportunities for the emergence of this knowing. We cannot escape this circularity. We cannot escape our embededness.

Self-Referencing

How plausible is the saying that "one man's meat is another man's poison?" According to Polanyi (1966) and Varela, Thompson and Rosch (1991), perception is co-created by the cognising entity (organism) and the environment. In the section above, we have just discussed how organism and environment co-specify or co-determine each other. Organisms are exposed to everything outside them. However; if that exposure leads to interactions that allow the expansion of the organism's cognitive domain or enhances the way the organism lives, then those interactions become part of the way that organism lives. Whatever works to sustain living in a setting is allowed. The organism's choice, in that sense, is self-referential. For instance, the level of toxicity of most chemicals varies to some degree for different organisms because for each organism, the history of interaction with the environment that contains the chemical is different. The structures of each organism and the world that the organism is part of have evolved as a result of this history of interactions. The qualities that the organism "ascribe" to each chemical are an interpretation or "transposition of bodily experiences into the perception of things outside" (Polanyi, 1966, p. 14). Therefore a stance taken on whether water or ethyl alcohol is toxic or not depends on the context and for whom. Experience with level of alcohol in human beings tells us that even within the same species, the answer is highly contextual. How does this analogy help us understand the processes of learning chemistry? The meanings that are created do not only depend on the environment external to the students, for instance, it is not only about copying and reproducing symbols and characters on paper; rather students are part of the context of meaning making. For those meanings to make a difference to the student, the student should be able to use them to re-organize their own life. Since our body is both the experiential structure and the milieu of cognition, the processes of meaning making, consequently, are self-referential (not removed from the body). The body knows and determines the type of risk it can deal with, sometimes without that knowing being formalised in speech or language. Interpretations are emotive, based on what the experiences mean to the body, whether they are chemical (at the cellular level) or psycho-social at the symbolic languaging level.

Co-emergence and Meaning Making

Knowing in enactivism is co-emergent with the knower, occurring in the body and mind, inseparably, through interaction of the whole being with phenomena in a setting. When we interact with our world or with phenomena, the interaction transforms both us and our world and a different world of significance is brought forth. The doing that takes place in the interaction changes us and the phenomena we interact with. In the interaction we are able to make new distinctions about us, our environment, us-acting-in-the-setting. Although our acting is local and contextual, different understandings or coherences emerge for us that may also be global. For example, our understanding of ourselves and the relations we live in may be changed for us; we now know we can do certain things that we could not do before. Expressions like, "Oh I am not so dumb after all!" or "How stupid of me?" may be uttered. Although these expressions uttered cannot be taken literally, they express a different understanding of our acting-in-that-moment. For each participant, the world of significance brought forth is different because it is largely determined by the individual's interpretation of the phenomenon and the history of interactions of each individual with their environment. The distinctions between mental and physical activities become fuzzy because all are inter-related and all are essential in knowing.

Since the evolution of events in every moment changes the history of interactions, every moment is a new moment and gives birth to yet another. As a researcher I have to recognise each situation in a class as a new experience that can bring a different level of understanding in my inquiry and in students' investigations. Every perturbation or occasioning whether it is a teacher talking to the class, a researcher entering student's territory or students discussing an issue or event alters the setting and students and all participants in turn are changed by it. Can I as a researcher, identify in students' action-speech-thought patterns, moments that point to emergence of different coherences? Can I identify and describe the processes involved in these transformations? If I can, what significance do they bring forth for me? Can they help my acting-in-the-moment as a teacher, researcher or resource pattern?

Structural Coupling

Knowing is not a representation of a pre-given world but a co-emergent phenomenon arising from the mutual specification of knower and world. Knowers create a world(s) as the world(s) creates the knowers (Varela, *et al* 1991). The knower and the known world are said to be structurally coupled since one can not exist without the other. Maturana and Varela (1992) describe *structural coupling* as the ongoing process in which individuals interact with their environment (including other individuals) to enhance the cognition and co-existence of all. In this process both the individual and the environment "act as mutual sources of perturbation, triggering changes of state" (p.99) or structure without destroying their organization (or relationship). Two individuals (student-student or teacher-student) are structurally coupled if their actions and behaviour trigger cognitive growth for the each other. "Coordinated communication about communication and the assignment of language to signify abstract concepts fall within the network of structural coupling" (Crawford 1997, p.7). The act of cognising or knowing is brought forth by the evolutionary interactions that emerge from the structural coupling of the knower with the setting. Therefore, in a setting where there are multiple resource persons how is the learning of chemistry affected? Can students in a chemistry classroom provide triggers for other students to begin to understand chemistry or is the teacher the only one capable as has traditionally been the case? Can open-entry settings provide occasions for the development of coupling at this level?

The idea of structural coupling has implications for our understanding of teaching and learning. Students need networks of action and communication to increase possibilities for their understanding. Therefore in exploring ways of broadening our vision in science education we need not leave any stone unturned. Both the students and the teachers have to recognise the need for tapping into other sources and for knowing where to find and how to use these sources. von Glasersfeld (1995) talking about viability and increasing outcome spaces said,

> Just as some ways of acting *[and knowing]* "work" and others do not, so some of our conceptual constructs and theories work and other do not. ...the fact that something works (is "viable") does not mean that it therefore is a representation of the "real" world that prevents other things from working. (von Glasersfeld, 1995, p. 25)

Enactivism proposes a definition of cognition from a biological point of view where cognition is seen as effective action by an organism that allows it to continue living or to co-exist with its environment. As Mingers (1996) stated, organisms are always having to undertake activity in order to continue their existence, to replace something that is lacking, to maintain constant some internal relation. It is this activity that Maturana and Varela (observers) described as cognitive even when it does not involve the nervous system. Contrary to normal usage of the word cognition, which limits it to organisms with a central nervous system, Maturana and Varela's (1987) definition includes all living organisms and sets cognition as a precondition to continuance of life. Thus defined, cognition completely eliminates the dualism between knowing and doing. Doing is knowing and knowing is doing. This idea is one of the cornerstones of this research. "Learning is coming to be understood as a participation in the world, a co-evolution of knower and known that transforms both" (Davis & Sumara, 2000, p. 64).

If knowing is doing, what is it that we do in high school science that, perhaps need to be re-examined? What ideas of knowing or learning are we currently using that can be extended or re-visited to enable us to teach science in ways that may reach out to more students than we are reaching now? Table 2 juxtaposes some positions that can be inferred from the constructivist epistemology in science education with those implied in enactivism.

I juxtaposed aspects of the two theoretical positions to amplify their complimentary and evolutionary tendencies and de-emphasized the contradictory trends. Whereas in Table 2 constructivism seems to focus on the form or structure and locus of knowing, enactivism focuses on the processes of knowing. The two positions presented in the table are different views of the same aspects. To understand the process of knowing we need to be able to view it from different perspectives. Whereas knowing can be seen as existing within a person it also arises in interaction. Human beings do not imbibe all the knowing from the context. The knowing stays distributed in the interactions between the cognising human being and his or her environment. The aspects highlighted in this table are complimentary and together portray the multi-layering and complexity of learning in science classrooms situations as I understand it at present.

Table 2

Perspectives on Constructivist and Enactivist Epistemology: School Science

Constructivism	Enactivism
Knowledge exists within a person (mind/brain)	Knowledge evolves from interactions, from the co-emergence of person(s) and from their world(s) and may exist in the body
Knowing and understanding are expressed in explanations (articulation)	Knowing and understanding are expressed in embodied action (knowing is doing and doing is knowing)
Constructivism focuses on symbolic and verbal forms of cognition	Enactivism focuses on embodied cognition that includes all action
Learners evaluate, reason and make decisions to accommodate, assimilate, reconstruct for themselves, reject or ignore concepts	Learners select energy-rich matter in interactions to create their worlds as these worlds also create them. In interactions, they learn, and make coherences for themselves
Learner-teacher-researcher are independent and do separate activities	Learner-teacher-researcher are complicit in learning/teaching. Each participates in the other's actions by providing triggers for each other (they are part of the context) in the process of meaning making but do not cause it. They are part of the braided mosaic called life
Environment is external or removed from the learner, or the learner's cognitive activity: it acts as a backdrop.	The environment is part of the context of meaning making, offering triggers with which a learner interacts to organise him or herself.

Having both views we can teach and design our interactions with students ensuring that we get the best of both sides. Table 3 adapted from Kieren (1997) highlights some of the teaching positions that have been employed in high school science and some that the new understanding of cognition point to for us to be able to offer a richness of experiences that students can benefit from in our science classes.

In my research although I focus on enactivism to guide my study, I acknowledge that we have learned considerably about students' learning from constructivism. The simultaneous co-evolution of the two schools of thought has given rise to our current understandings.

Table 3

Comparison of Teaching Positions in High School Science

	Teacher place and world view	Teaching possibilities	Teacher's view of curriculum and the body of science	Teacher pedagogy and action	Nature of discourse and goals	Evaluation
Traditional Representation	In front of class An externally pre-given world	one correct scientific	reflects the correct scientific world	preplanned presentation with teacher talk, reproduction and remediation	unidirectional, uniform conforming to one scientific view	prescriptive; teacher checks, looks out for or listen for correct or best answer
Constructivist emergence	in front of student or over the shoulder An internally constructed world view	a correct scientific outcome, individual construction and conceptual change	facilitate student's construction to match with scientific view by finding bits of appropriate curricula	set up context and facilitate individual constructions, discrepant events cognitive dissonance, analogies	supportive, focusing on logical understanding, and elaboration of abstract concepts using personal constructs	semi-prescriptive teacher listens to students' portrayals and supporting arguments and compares with existing body of science
Enactivist co-emergence	Teacher exists besides and brings forth a world of science with students	Multiple possible scientific answers and pathways. teacher creates opportunities, keeps open and listens for new possibilities	curriculum is enacted, lived, complex and dynamic students also co-participate in the contemporary practices and bring forth a world of scientific significance	co-emergent, context bound co-participation with students. Teacher invites and listens with students	interactive, exploratory, creative and explanatory bringing forth relations, coherences and worlds of significance with others	proscriptive; teacher listens with students to bring forth a world of scientific significance

CHAPTER THREE

RESEARCH IN CHEMISTRY EDUCATION

Research in high school chemistry education since the 1960s, focused mostly on the content of chemistry or subject matter which was divided and into concepts. What is a concept? The word concept brings up notions of idea, theory, thought, perception and generalization. According to Fensham (1975), a concept as used in chemical education is a generalization of some sort. This generalization may be at multiple levels. A concept can also be described as a powerful idea that defines how we describe or structure our understanding of chemical systems or chemical phenomena. This includes: structure, bonding, reaction rates, chemistry, technology and society, a class of objects with common features such as mole, acid, oxidizing agent or a pattern of behaviour linking similar chemical or observed properties or statements of relations that link concepts. What do we mean by conceptualising? "Conceptualising is a process of filtering reality *(or of creating and marking coherences)* and we need to remember this at all stages of our learning chemistry" (Fensham, 1975 p. 215). The initial focus of the chemistry education research was on identifying and recording students' learning difficulties. Concepts such as the mole, oxidation-reduction, organic chemistry, stoichiometry and electrochemistry became particularly interesting to researchers because they persistently posed a problem for high school students and teachers world wide. Most of these concepts deal with or are based on highly theoretical and abstract ideas removed from students' every day experiences and are often taught without the use of laboratory activities to help students understand. To learn them students memorise and do a lot of drill paper and pencil exercises and the typical approach to teaching these concepts is lecturing, giving notes, homework and tests.

In Scotland, for instance, Johnstone's (1983, 1984), Duncan and Johnstone's (1973) and Johnstone, Morrison and Sharp's (1971) research involving Nuffield chemistry programs dealt mainly with the mole, trying to find ways of making it simpler and more accessible to students. In England, Gower, Daniels and Lloyd (1977), and Lazonby, Morris and Waddington's (1982, 1985) work on the mole reflect the persistence of difficulty and concern about teaching it. While in Canada Griffiths and Kass (1981), and Griffiths, Kass and Cornish's work (1983) on the learning hierarchies of the mole tried to develop strategies that could help teachers teach these difficult concepts. In Israel, Novick and Menis (1976) investigated children's conception of the mole. In their study involving 15 year old Israeli students, they found that students had various conceptions of the mole. Some thought that a mole was a certain mass not a number, others thought a mole was a certain number of gas particles while others thought that a mole was a property of a molecule. In Italy, Cervellati and Perugini (1981), and Cervellati, Montuschi, Perugini, Grimellini-Tomasini and Balandi's (1982) work on the atomic structure and the mole concept, respectively, also reflected the extent to which these concepts were problematic. Students either did not answer questions involving the mole or if they did, their answers were incorrect. In Sweden, Stromdahl, Tulberg and Lybeck's (1994) and Tulberg, Stromdahl and Lybeck's (1994) phenomenographic research on the mole reflected the qualitatively different conceptions of the mole that both students and teachers had.

In Australia, Fensham and West (1976), for instance were exploring whether it was prior knowledge or advanced organizers that helped students learn high school chemistry. Their work over several years, 1972 to 1976, showed the importance of prior knowledge in learning chemistry. Fensham (1985) and the Monash group continued to work extensively on students' conceptions (alternative frameworks) in school chemistry. Many of the concepts in high school chemistry that students had difficulty with also involved using mathematics.

In the Netherlands, Kramer-Pals, Lambrechts and Wolff (1982), investigated recurrent difficulties in solving quantitative problems. In Germany, Schmidt (1973) studied methods of quantitative analysis in high school organic chemistry and continued in later years to explore how students' conceptions and conceptual background knowledge (1990, 1991, & 1997) influenced students' success in problem solving. His 1990 study of stoichiometry showed that students' lack of conceptual knowledge base was a major impediment in quantitative problem solving. It revealed that students often equated "amount" or "molar mass" with reacting mass. Schmidt concluded from his study (1998) on students' use of LeChatellier's principle that students tended to explain chemical phenomena based on very limited understanding arising from memorization. From his study he suggested that LeChatellier's principle should not be taught in school because it is more complex and difficult to fully understand at that level.

In the United States, Gabel and Sherwood's (1984), and Gabel Sherwood and Enochs' (1984) investigated students' work on the mole and quantitative problem solving. Bunce and Heikkenen's (1986) research on quantitative chemistry problem solving also focused on specific high school chemistry subject matter. The research I conducted (Buthelezi, 1987) in Botswana revealed that the same subject matter content was problematic for high school students there also. The content of high school chemistry is mostly contained in textbooks which tend to define the curriculum. A brief look at how these curricular materials have traditionally been developed may shed some light on the path we have embarked upon.

Textbooks and the School Chemistry Curriculum

When you talk to high school chemistry or any science textbook authors for that matter about the quality of the book, often their number one concern is with publishing. Publishers often modify and/or remove large chunks of written text and illustrations to cut production cost so that the book is marketable. Herron (1983) observed that the content, organization and development of chemistry texts were greatly influenced by market research which tended to guarantee that curriculum materials did not change. Lloyd (1992) stated in his review of curricular change in general chemistry in the US that despite many curricular reform efforts, there had been little change in the implementation of these curricula. "The most obvious example of this resistance to change appears in the popular textbooks used today in general chemistry. What began as a compendium of facts about chemical elements has become an encyclopaedia of principles and their applications" (p.635). The politics of textbook writing and publishing, in a field that has vast amounts of information and has developed so rapidly, tend to override some of the educational intents. Therefore, a significant amount of sensibly practical information that can help in the making of connections between concepts or even between experience and concepts is left out in favour of what is deemed "the knowledge of most worth." Historically high school chemistry textbooks were written by university professors and specialists in the field who held very sophisticated understandings of the discipline and were more inclined to focus on abstract principles and concepts. Harrison's (2001) study of model usage by teachers and textbooks revealed that there is a significant "difference between chemistry teachers' sparse repertoire of volunteered models and the plethora of models found in their textbook" (p.427). Chemistry textbooks use many models but only identify a few as models, leading teachers unable, perhaps, to categorically identify these models. The result is that they are not addressed in class as models and their limitations are never discussed with students. Students are therefore left with fragmentary understandings.

In an attempt to capture as much of the accumulated body of chemical knowledge as possible, the authors tended to distil this knowledge to cover much of what they considered important, the theories and laws, with very little detail given. Due to the vast numbers of concepts, theories and laws to be covered within the two to three year span of high school, the curricula became quite rigid. This was at times exacerbated by teachers' lack of familiarity with the concepts which limited their teaching approaches. Consequently, the teaching of the subject reflected this bias which in most cases involved mathematical thinking with the assumption those students would be able to understand and connect them to their experiences of phenomena. "From the simple suggestion that linear relationships should be used to give students confidence in the use of mathematics to express laws and principles," continued Lloyd, " has come hundreds of math problems that leave students believing the process of solving word problems is the same as learning what chemistry the problems represent" (1992, p. 635). Some of the common oversights arising from this assumption are:

- neglect of the chemical phenomena that led to the development of these laws and principles
- neglect of the processes by which students develop an understanding of the laws and theories
- neglect of the changes in the meanings associated with the laws and the principles within chemistry as this field develops
- neglect of the changes in the meanings as the student's chemistry knowledge develops.

This often results in students being told and thereafter expected to have a sophisticated level of understanding so that they can manipulate the concepts in formalised and abstract paper and pencil situations. The appreciation of these theories and laws not only requires an ability to deal with abstractions but also some basic intuitive forms of knowing which can act as a link to the students' experiences of phenomena (Fensham and Marton, 1992). For students to begin to make sense of the chemical laws, principles and theories, they need to have chemistry experiences that engage their whole being and demand independent thinking and decision making. They also need experience in a variety of settings with the chemical phenomena on which the theories and laws are based. Fensham (1975) in his discussion of concept formation in chemistry noted that "concepts are introduced and defined before their usefulness is or could be apparent. Without application of a concept, the learner can only respond to it by rejection or rote learning." (p.202). In other words, these concepts are presented in ways that do not give students a chance to playfully linger with events that could foster conversations and formulation of ideas that could establish the relationship between lived experience and the generalizations made of these experiences. The concepts, which are in themselves condensed, abstract descriptions or interpretations of a series of activities are presented as bare generalizations without any history of how they were arrived at ever made known to students. Meanings derived from such presentations are limited and their usefulness often ends with the examinations. They do not help bring forth a personally meaningful world of significance for the learner (Rop, 1999).

Research is needed that can help us transform our teaching to help students make personal meaning of their learning of chemistry. The braiding in and juxtaposing of my experiences as a student and a teacher of chemistry with accounts of students' experiences along with those of the chemistry teacher I worked with in this study may help us learn more about this phenomenon.

The Teaching and Learning of Chemistry Concepts

Movements in research aimed at improving the teaching of school science in the UK and the USA in the 1970s and 1980s were strongly influenced by interpretations of Piaget's developmental psychology. Attempts to match learning and cognitive demand of subject matter to students' developmental level were frequent (Adey & Shayer 1994; Niaz, 1996; Shayer & Adey, 1981). These matched programs and/or units were then presented as prescribed with matching written tests to measure the outcome. These efforts although helpful in teaching us more about the nature of learning, did not make learning easier for students. More was needed to understand students' learning. Why were students not changing their conceptions of the world to be more like those of teachers and scientists? Focussing on children's ideas in science classroom gave birth to the conceptual change movement in science education.

In the recent past, from the nineteen seventies onward, following Ausubel's (1968) ideas of meaningful learning and Driver and Easley's (1978) research on children's science, research driven chemical education in high school has focussed mostly on finding students' alternative (sometimes also referred to as misconceptions, pre-scientific conceptions, naive beliefs, preconceptions) conceptions. If these were identified, strategies for helping students change them could be developed and used in classroom teaching. From a constructivist point of view, we can not effectively teach students if we do not know where they are or what they already know about the ideas we intend to teach, hence the move to try to identify these before introduction of new concepts. Several studies have focussed on students' conceptions and conceptual change in chemistry. Students' conceptual difficulties have been identified in electro-chemistry, stoichiometry, bonding, chemical equilibrium, solution chemistry. Different strategies have been developed and used in classroom to enhance conceptual change. These include the use of metacognitive strategies where students, have to develop an understanding of their own learning. These strategies emerged from Ausubel's ideas of meaningful learning and assimilation. For example:

- Concept mapping (Novak and Gowin, 1984, White and Gunstone, 1992)
- Vee maps developed (Novak and Gowin, 1984, Wandersee, 1987)

Other strategies developed from Posner, Strike, Hewson and Hertzog's (1982) ideas of cognitive dissonance to facilitate students' accommodation of new concepts. Some examples include using:

- Discrepant events (Hewson and Hewson, 1983, Fensham and Kass, 1988)

- Predict-Observe-Explain (POE) and Predict-Explain-Observe and Explain (PEOE) (Baird and Mitchell, 1986)
- anomalous events or exceptions

Treagust (1993), Harrison and Treagust (1993) and Harrison (1996) have studied the use of analogies in teaching science. They are used as explanatory tools to highlight the similarities of ideas or models and the concepts and or processes studied.

- multiple models describing theoretical concepts
- role play
- historical and biographical accounts.

Research in high school chemistry has also looked at student attitudes and dispositions in the study of chemistry. (Nay & Nadeau, 1985; Blackwood-Malayko, 1992). Other research on high school chemistry teaching and learning has focussed on teacher's knowledge and beliefs (functional paradigms) as well as the language of chemistry (Lantz, 1984).

Among other factors, the two that have strongly influenced the approaches to investigating students' understanding of school chemistry have roots in mathematics and physics education. The strong bias towards mathematical concepts in chemistry, probably emerging from the difficulty students encountered with the mole, stoichiometry, electro-chemistry, gas laws and the problem-solving approaches used in mathematics and physics resulted in the research in chemistry concentrating on paper and pencil mathematical problem solving. The approach was so ingrained in chemistry teaching to the extent that even when there were no mathematical ideas in the subject matter, paper and pencils tasks were deemed adequate for developing the understanding of concepts. Chemical education research reviews by Gabel and Bunce (1994) and Herron (1990) reflect this emphasis in the studies cited. Although problem-solving, in its broad sense, has a potential to capture the complexity of learning-teaching, and allow use of diverse strategies and can cover and integrate a wide range of content areas for both research and teaching-learning, its historical link to mathematical problem-solving and physics in chemistry has tended to restrict it to strategies and content areas that have a strong mathematical emphasis and that could be evaluated by using paper-pencil tasks. We therefore need to refine and redefine our notions of problem solving in school chemistry to be able to open up possibilities for the practice of teaching problem solving.

The Problem With Problem Solving in School Chemistry Education

Problem-solving often finds its meaning in its use and therefore it may mean different things to different people. In a simplified way, problem-solving is an activity that attempts to resolve a situation in which an answer is not known or immediately apparent. The most meaningful and useful question in learning is the question with no answer or whose answer is not known by anyone. That type of question can lead to problem-solving whose boundaries are embedded in and limited by the question itself and/or the histories of those asking it. Such a question therefore has a potential to open up space for enacting many problem-solving possibilities.

Mathematical problem-solving has greatly been influenced by Polya (1945) who described a method that was greatly embraced which laid out logical steps for solving problems. Polya's (1945) heuristics involved in order the following steps

- study, analyse and understand the problem
- devise a plan

- carry out the plan
- look back, check whether your solution makes sense

For numerical manipulations, this seemed sufficient and was reported successful.

High school chemistry problem-solving, following the tradition of high school physics and mathematics has been confined to paper and pencil quantitative problems. With this approach, students were given well defined problems with all or almost all the necessary information provided for them. This approach focuses on the results or end products and not necessarily the process of problem-solving. The problem with this approach is that it can be dehumanizing since it focuses only on individual mental processing of information, reducing a complex, social human being to a brain. This assumes that humans solve problems independent of others, in a linear, logical approach similar to computers. This approach is limiting because it leaves no room for creativity or self-expression and emphasises routine work that can be memorized. Studies emanating from this approach are limited in scope, tending to be more comparative. They compare, for instance, novices and experts' problem- solving skills. Innovations in teaching derived from these studies tend to focus on strategies of how to make novices more like experts and more examinations-ready. The development of the learner's personal meaning is not essential or is of no consequence as long as one obtains the right answer.

One would assume that the main aim of problem-solving as an approach towards teaching-learning and investigating students' understanding of concepts and processes is to learn from doing, not only from reading how to do things or working on paper and pencils tasks. The development of a personal and meaningful understanding of chemistry emerges out of physical experience and doing things with chemistry especially in the introductory phase. In addition, problem-solving seems to have potential to demonstrate to both students and teachers the complexity and dynamism of the discipline. The processes of finding a workable solution to a problem are varied and in most cases the solutions too can be varied. The virtues of problem-solving as an approach that serves to motivate students develop critical thinking and make learning more relevant and meaningful to students can not be overstated. For a curriculum that places heavy emphasis on abstract concepts, theories and principles, mathematics is of utmost importance. As Craig (2001) put it:

> The range and level of use of mathematics needed for chemistry is enormous. It extends from the relatively modest levels used by synthetic organic chemists through greater use by inorganic chemists and biochemists to extensive use by physical chemists, computational chemists and theoretical chemists. For theoretical and computational chemists the level and uses are without limit. . . . For all the subfields within chemistry there is dependence on thinking quantitatively and on using spatial models of molecular systems. (p. 582)

For many students, high school chemistry would be the last chemistry course they take in their formal school education and therefore they would not use any of this highly abstract computational chemistry.

Problem-solving in high school chemistry has historically tended to be synonymous with quantitative paper and pencil exercises because of the focus on abstract concepts in school chemistry. As result, a significant amount of chemistry education research has been on quantitative problem-solving in both high school and higher level chemistry. An example of a problem-solving chemistry textbook that has been in use for a long time is *Solving General Chemistry Problems* (Smith & Pierce, 1955), first published as *General Chemistry Workbook*. The book was designed for entry level chemistry and was still in use less than a decade ago. Some of its key features are as follows:

- It is designed to be used with the calculator (*the fifth edition)* - a new technology. Earlier editions were designed for use with the slide rule and log tables.
- Problems in the textbook have answers worked out, some of which are provided at the end of the student textbook, answers for the rest are in the teacher's edition
- Every section has worked-out examples that the student can copy and learn the algorithm from
- It has a section giving instructions on improving particular problem-solving skills
- Its emphasis is on drill, drill, drill. Students are encouraged to work on hundreds of problems and to cross check their answers with those provided. They are also encouraged to keep working at problems until they are able to reproduce the answer provided by the textbook.

This approach to problem-solving focuses entirely on paper and pencil work. Advocates of this study skill focus on problem analysis. Students have to learn to recognize problem-types and memorize ways of solving those types of problems. Teaching is predominantly chalk and talk where students are expected to study class notes, the textbook and be able to fully understand the facts and principles thus taught.

Generally, as educators schooled in a modernist world, we are more comfortable with problem solving as it exists because we know the answers. The answers are out there, through established strategies or routines we can find them. The student's role is therefore clear-cut, they have to learn to mimic the teachers and memorise strategies for solving these problems. The enactivist stance, however, demands of us that we leave our comfort zone of known answers or certainty and venture into unknown territory, to stretch the boundaries of what is possible and what is an acceptable demonstration of knowing. The confidence we have is that as we enter into this our culturally shared world, it is the established history of co-existence, the dynamic nature of living, interacting and creating spaces for each other that will guide us to be and allows us to live as holistic, non-fragmented knowers who not only know themselves but also know what they know and can anticipate the consequences of their action.

Table 4

Problem Solving

Paper and pencil	Physical materials "at the bench"
Mostly mental with limited physical involvement	Mental, physical, emotional, multisensory
Linear, sometimes complicated, with possible single feedback loop distanced from real physical phenomena and therefore not informed constantly by phenomena	Complex, reiterative with multiple feedback loops at multiple levels the practical situation speaks back at every step forcing learners to focus, look back, look around, rethink, redo and be on the alert
Possible to pursue lines of thought unconstrained by phenomenon and to come up with solutions that seem reasonable and not practical for given situations	Viability and practicality of solutions become manifest immediately Action to address unproductive approaches can be implemented immediately
May lead to a limited sense of the discipline and can easily become routine	Always calling for self input and therefore can be motivating

Few studies in the science education journals describe students' success in learning high school chemistry (Harrison, 1996; Rop, 1999). Those who become successful, develop a far more holistic personal understanding than the less successful. However, according to Rop (1999), "from the first impression, it seemed that the grade was the only thing of importance to students. Disciplinary knowledge at first seemed almost incidental and only loosely connected to successfully getting a good grade" (p. 228). As he continued his study he discovered that some of these successful students did not only strive for grades but also wanted to understand it, to use their own words, for their "personal well-being". Students appreciated that success in chemistry required more work than what was required for good grades, it was personally rewarding and challenging to the self as well. This research suggests that some students are able to recognize the complexity of the discipline and appreciate that there is more to chemistry than what is presented in school. We therefore need to broaden our conceptions of high school chemistry so that more students can also develop this appreciation.

Broadening Problem Solving in School Chemistry

Laboratory activities have long been considered an essential component of high school science learning (Lunetta, 1998; Hofstein, 1988; Gabel, 1994). Tobin (1994) gave an extensive list of research and research reviews done on school science laboratories in different countries. What do we wish students to learn in and from the laboratory? The goals for science education broadly categorized are that students should: learn concepts, theories and facts of science, learn about science and develop an appreciation for the nature of science, science processes and STS and for students to do science, where they engage in scientific enquiry and develop skills and expertise in doing science. Laboratory activities can be designed to address these goals. However, not many traditional science activities have been able to teach the last two goals successfully. The laboratory activities accompanying the 1960s curricula materials were designed to teach scientific inquiry where students were expected to discover for themselves theories and principles used to explain natural phenomena. The failure of these laboratory reform efforts to teach scientific inquiry and concept building resulted in many educators being sceptical about their worth and effectiveness. The general tendency was to shift focus towards known recipe type activities which could be used to illustrate concepts already taught. Hodson (1996) argued that although emphasis was put on laboratory work aiming at teaching students the processes of scientific inquiry, approaches to laboratory work used over the years were confusing and distorted the nature of scientific inquiry. What seemed questionable though from the review of literature were the assumptions made about learning and also about scientific inquiry. Scientific inquiry is not purely inductive and neither do children learn only by discovery especially in unfamiliar contexts like the science laboratory. Another criticism put forward against earlier attempts at incorporating laboratory work successfully in school science was that scientific inquiry can not only be reduced to a method or to a few processes that are usually used to describe the scientific method. Science and scientific inquiry are not value-free. All processes involved are theory laden.

> Being able to carry out one, or several, decontextualized tasks focusing on observation, classification or measurement says very little about one's capacity to conduct real scientific investigation. Indeed it is sometimes the case that students who are able to perform adequately on such decontextualized tasks are unable to integrate these skills and abilities into a coherent and effective strategy for scientific investigation. Conversely, many who perform poorly in these sanitized tests can engage interesting and successful scientific inquiry when they are

> suitably encouraged and given freedom and support to follow their interests. (Hodson, 1996, p 125)

Science educators have debated the effectiveness of school science laboratory work in helping students learn science concepts. It would seem that the controversy arises from wide variety of goals laboratory work seems to be aimed at (Hofstein, 1988, Hodson, 1996, Roth 1998, 1999, 2000, Woolnough, 2001). If as Hodson (1996) suggested that the apparent failure of laboratory work in high school was due to ill-defined and confused goals, there is an urgent need to closely look at these goals. Hofstein (1988), after coming to the conclusion that

> it is true that research has failed to show simplistic relationships between experiences in the laboratory and student learning in science. Furthermore it is unreasonable to assert that the laboratory is an effective and efficient teaching medium for achieving all goals in science education (p. 212),

suggested that there was a need to refine and redefine the goals and to search for or develop teaching strategies that would achieve the desired goals. Lunetta (1998) in his analysis of research done on school science laboratory concluded that "Classroom based studies reveal that the mismatches between goals, behaviour and learning outcomes ... continue to limit the effectiveness of the laboratory in science teaching" (p. 260). A recent study reported by Sere (2002) funded by the European Commission and involving research groups from six countries in Europe, suggested that within these countries there was still need to select and clearly redefine the goals for high school laboratory work. Curricula materials developed in Alberta seem to have made headway in this respect in the sense that they have been able to narrow down the goals and differentiate between scientific problem solving and technological problem solving. With goals clearly defined, teaching strategies can now be developed and tested. One such strategy suggested by this research is using open-entry problem-solving activities.

Much research has focussed on open-ended activities in teaching science inquiry (Boud, Dunn & Hegarty-Hazel, 1986; Roth, 1995, 1998, 2002; Reid, 2002a, 2002b) over the years. It is argued that these types of activities teach students to appreciate the processes of scientific inquiry and help motivate them to learn science (Kozlow & Nay, 1976; Martinez & Haertel, 1991). However, this approach still maintains the teacher or the text as the main problem poser. Students in a sense are given a problem. An alternative that is offered by this research is open-entry activity. This approach to inquiry involves students in all the planning of the investigation. A prompt is offered to students from which students can derive a research or investigation problem based on his or her interpretation and understanding of the prompt. Because of the different histories and understanding that students bring to the activity, their problem statements, designs and actual carrying out of the activity differs. Their entry to the problem is varied and open to that difference. Martin-Hansen (2002) in her paper identified three types of inquiry: open or full inquiry, guided inquiry and coupled inquiry which are different from cookbook type or structured inquiry. She offers these as different approaches teachers could use to teach science inquiry. This still leaves room to question the practicality of the approach for teachers considering teaching inquiry.

Starting in the 1990s there has been growing interest in personally meaningful science in science education discourse. Authentic science, doing science, real-world science, scientific inquiry, open-ended hands-on investigations, open-ended inquiry, problem-solving, design-based science learning, variable/open-entry investigations, miniprojects, project based science, technological design problem solving, self-directed problem solving are contemporary words in both high school science and mathematics education research. They are used in different countries and different contexts but they all describe, in science, activities that are designed to engage students to personally find meaning in doing science. The emphasis in no longer just in learning science concepts or learning about science concepts but also in doing science. Research into students' ideas and perspectives on science revealed that many students felt that the science they were learning was not relevant to them (Blades, 1992) because students could not find any personally meaningful coherence from them. This along with more global concerns to find personnel qualified in science to work in the various sciences and science related careers and also to educate a scientifically literate populace has resulted in a search for meaningful science in schools. Other research uses terms like 'authentic science' (Roth, 1995; Brouwer, Martin & Kass 1998; Blades, 2000), 'naturalistic science' and 'scientific inquiry' Chin (2003), National Research Council (1996), National Science Teacher Association (2000), to describe laboratory activities that are designed to draw in students and engage them in doing science.

Descriptions of science/scientific inquiry have identified the following four phases:

- Focussing: The design and planning phase involving recognition of a problem, formulating a problem and stating it in a testable form, generating hypothesis and devising procedures and techniques to use towards solving the problem

- Exploring and investigating: the execution phase involves gathering materials and testing of carrying out of the plan devised using materials gathered and gathering data for analysis
- Reflecting: the reflection phase involves a careful consideration, interpretation and analysis of the data or test findings
- Communicating: this final phase involves evaluating products, materials and processes and recording and reporting these evaluations for communication with others

Although this structure may be useful in describing some of the major components and seems convenient, doing science is not linear and straight forward as the description above may seem to suggest. The phases are not separate. They may occur all-at-once or in any combination in the process of doing science. Since different researchers bring different histories and understandings to their research, their plan of action and the constant redefining of the process as one tests and retests their ideas also differs. There is no one method of investigation. The entire processes are complex and iterative as the researcher constantly gets immediate feedback from interaction with physical materials (Hodson, 1996). This research aims at describing, interpreting and explaining some of the processes students use in open-entry high school activities.

CHAPTER FOUR

A WORLD OF POSSIBILITIES

> When we look at the universe on size scales ranging from quarks to galaxies, we find the complex phenomena associated with life only at the scale of molecules. Why? . . . One answer is just to say "chemistry," life is clearly a chemical phenomenon, and only molecules can spontaneously undergo complex chemical reactions with one another. But again, why? What is it that allows molecules to do what quarks and quasars can't?
>
> Two things, the first source of chemistry's power is simple variety: unlike quarks which can only combine to make protons and neutrons in groups of three, atoms can be arranged and re-arranged to form a huge number of structures. The space of molecular possibilities is effectively limitless. The second source of power is reactivity: structure A can manipulate structure B (*or vice versa*) to form something new—structure C. (Waldrop 1992, p. 314)

In the above quotation Waldrop was trying to impress upon our awareness that there is endless meaningful, creative power and possibility in variety or difference. When we curb or curtail that difference, we are in effect limiting our creative possibilities. Can this observation made of chemistry inform our teaching of chemistry? Perhaps!

According to Bruner (1990), meaning making involves situating personal encounters with the world in their appropriate cultural contexts in order to know what they are about. In this chapter I discuss the culture of high school chemistry to elucidate the context within which this research is embedded. Bruner (1990) said, "It is culture that gives meaning to action by situating its [the action's] underlying intentional states in an interpretive system" (p. 34). Therefore, to understand school chemistry we have to know something of its culture and situate it within the context in which it evolved. I briefly discuss the culture of science and the culture of the school to illustrate aspects of this evolution.

Is chemistry a ritual, a fixed practice, or a survival tool in an evolving life? This question along with the implications it has for chemistry classrooms is pertinent and worth considering in the practice of science education in our changing and diverse societies and environments. School chemistry has changed very little in the past century from an elitist subject designed for the few who can appreciate the dynamism of the discipline. Despite the tremendous growth in the field of chemistry, its cross-disciplinary scope, and the multiple ways it impacts on the lives of every human being, few students leave secondary school with an understanding of its impact. Realizing this condition, in the United Kingdom, for instance, developers have aimed recent developments in school science curricula at "keeping school science in step with the changing world of the 21st century" (Holman 2001; Holman & Hunt 2002; Osborne & Collins 2001).

An examination of the culture of school chemistry reflects that it not only tends to make chemistry meaningless for students, leading to rote learning and memorization, but it also creates a "monster" out of chemistry and thus may alienate students. What are the current pedagogies, practices, and expectations in high school chemistry; and how do these influence a student's understanding of the role and function of the chemical sciences? Evidence will be drawn from my teaching experience and that of other chemistry teachers with whom I have worked as well as from research conducted over three years in high school chemistry classrooms. My position is that if chemistry is a tool with which we make sense of our living in the world with others, then it should be able to help students cope with their evolving lives. It should, therefore, be dynamic. The culture of school chemistry learning and teaching should reflect this dynamism.

Culture can be broadly described as the beliefs, behaviour, language, and way of life of a particular time or group of people. It includes customs, ceremonies, works of art, inventions, technology, and traditions. It may also be described as the total integrated pattern of human knowledge, behaviour, and belief that includes thought, speech, action, and artefacts and depends on our capacity for learning and teaching succeeding generations. Both definitions describe culture by its attributes. Although it is common practice in academic discourse to characterize complex phenomena by their attributes, it is worth bearing in mind that these phenomena cannot be reduced to simply the sum of their attributes. With this reservation in mind, can we identify a distinct school chemistry culture? Can we identify behaviours, beliefs, customs, ceremonies, inventions, technologies, traditions, and language that are distinct to school chemistry so that we can talk of the culture of school chemistry? How could this culture be related to the culture of the school and that of chemistry as a scientific discipline?

The Culture of Chemistry

Sacks (2001) acknowledged that his experience with different artefacts of chemistry including the periodic table and chemistry books and with the practices of chemistry—in others words, his experience with the culture of chemistry—transformed him. It changed his way of seeing and being in the world. He wrote:

> Reading Dalton, reading about atoms, put me in a sort of rapture, thinking that the mysterious proportionalities and numbers one saw on a gross scale in the lab might reflect an invisible, infinitesimal, inner world of atoms, dancing, touching, attracting, and combining. I had the sense that I was being enabled to see, using the imagination as a microscope, a tiny world, . . . the actual constituents of matter. (p. 150)

In this section I offer a description and an account of the culture of chemistry that would allow us to see how Sacks' (2001) experiences were possible and that, in turn, would suggest an explanation for students' meaning making. Chemistry is a complex, multifaceted science that focuses on trying to understand the composition and properties of matter and its behaviour in our world. Like other disciplines, the evolution of chemistry is based on observation, logic and rationality. It studies the origins, uses, and interactions of different substances; for example, how different substances change from one form to another to create new materials. Chemistry's success in creating explanations and predictions involves some phenomena that are accessible and others that are not readily accessible in everyday experience. Chemistry has as one of its basic assumptions that the material world, which is complex, can be analysed and understood by breaking it down into its elemental constituents with discrete properties and attributes. Systematization, classification, and building of structure around and about chemical knowledge are the order of the day. Rosser (1995) described chemistry as follows:

> Chemistry has its own culture, or perhaps what might be better termed its own set of mini-cultures. Chemists share a number of things, including a core of scientific knowledge ("truth"), a system of symbolic representations, a technical language, professional behaviours and values, preferences about how the discipline should be organised. . . . Chemists may even share a dress code. (p. 86)

The practices of chemistry are multifaceted, complex, and nonlinear. The formal and publicly shared accounts of chemistry research have, however, appeared to present these practices as if they were clean, linear, and easy to follow. The differences in the practices, processes, and outcomes of inorganic, physical, theoretical, and organic chemistry seem to support Rosser's (1995) claim. However, high school chemistry, which comprises mostly inorganic chemistry, is more homogenous and has over the years tended to develop a more uniform culture. Schooling, broadly considered, is based on the belief that knowledge and tradition are valuable for the success of the human species and should be passed on to new generations. Another belief on which schooling is based is that human beings learn and can be taught. School chemistry has inherent in its constitution properties from both practices.

The Culture of High School Chemistry

High school chemistry often finds itself having to work within the constraints of the general school structure; for example, 40-minute or sometimes 80-minute class periods, local and national curriculum specifications, and the specified range of equipment and materials available. The merging of the chemical sciences and schooling has resulted in properties and attributes of school chemistry that are distinct from the "parent" practices. For instance, in the practice of pure chemistry there is a general understanding that knowledge is not fixed or complete (a tentative, nondualistic view)—an understanding that is essential to research and development but which seems for the most part to be missing in school chemistry. Rather, school chemistry is presented as a rhetoric of conclusions (Schwab, 1974) in which the student does not participate. As Finster (1989) put it, "Dualism in science is but a convenience offered by situations upon which scientists agree; only then do we see right and wrong. Yet it is from this simplified vantage point that we see much of [high school] chemistry presented" (p. 660). Current views of cognition suggest that for the learner, schooling may be as much about the construction of a "self" with a personal history and a projected future as it is about acquisition of a "toolbox" of knowledge and skill (Bruner, 1996; Varela, Thompson, &

Rosch, 1991), and school chemistry should be able to provide opportunities for this development.

The Content of School Chemistry

In the 1840s school chemistry in the United Kingdom focused on that chemistry that would help students understand better their everyday experience of phenomena (Ingle & Jennings, 1981). It was descriptive and applied with respect to the technology of the day. However, with the changing social demands, increased technological sophistication, and rapid knowledge accumulation of the 20th century, the nature of school chemistry has changed. It has become theoretical, abstract, conceptual, and, for that matter, boring and uninspiring, as succinctly described by Sacks (2000), who had experienced a world of wonderment and excitement in his early childhood chemistry explorations. By the early 1960 s in the United Kingdom, for instance, curricular reforms that recognised the need to "reduce the amount of, and bring up to date the factual side of subjects" and to "emphasise important principles and skills in scientific thinking" (Ingle & Jennings, 1981, p. 23) were underway. The extent of these movements spread worldwide as the curricula materials were either exported or translated into other languages (Chinese, French, Gujarati, Hebrew, Hindi, Italian, Japanese, Korean, Spanish, Thai, Turkish, Portuguese, and Russian) for use in other countries, including the Commonwealth countries (Brock, 1992). A brief reflection on the curricula changes that took place is shared in the following excerpt from an interview with the chemistry teacher with whom I worked:

> Researcher: What we would like to talk to you about [name of teacher] are some of your reflections about how chemistry curriculum, in your judgement within the twenty-five years that you have looked at chemistry curriculum

critically, how chemistry curriculum has changed. Do you want to scroll back to — ?

Teacher: When I was in high school I was kind of brought up in the technological approach to chemistry. We had a quantum mechanics supplement.

Researcher: What year would that be?

Teacher: That would be 1962 when I was in Grade 12. While I was in university . . . was when CHEM Study was being promoted along with PSSC. I can remember that as I was going through university I also had to intern a number of years and the thing that I was quite often given as a task was to teach this quantum mechanics supplement in the Chemistry 30 course. The older teachers did not have this background. I can remember teaching the enquiry approach, the kind of thinking that was being promoted, discussions about how are we going to find answers.

Researcher: So all the stuff that you liked in school, the metallurgy and application, that was gone, that's toast?

Teacher: Yes, yes it was totally gone. At Grade 11 level, I mean, we were teaching "spdf-type" of electronic configurations and going into quantum mechanics in gory detail, and I can remember because I had a pretty good background including a modern physics course —

These developments created a school chemistry culture in which students' engagement with chemistry involved absorbing and giving back what was given. Classroom practice became removed from the students' life encounters. Laboratory work became highly structured, rigid, and recipe-like and used to illustrate and/or consolidate concepts already introduced. For the theoretically inclined students, the changes are a success. Fensham (1984) claimed, "In many countries, there do now exist much improved courses for educating in chemistry those pupils (about 20% of any school age) from whom the future chemists and other science based professionals will come" (p. 1). The concern raised by Fensham 18 years ago that school chemistry was not serving the 80% of the learners who were not likely to study chemistry after leaving school is increasingly relevant today because, more than ever before, chemistry is revolutionising our world and our lives. Sorting and preparing students for university are still very pronounced despite curricular reform guidelines that stated that the curriculum "should be equally suitable for future science specialist, for those who would later specialise in other subjects, and for those who would leave school early and take up non-academic careers" (Ingle & Jennings, 1981, p. 22). Recent curricula reforms in the UK and the US are aimed at developing school chemistry programs for citizenship (Holman & Hunt, 2002; Moore, 2002).

Chemistry can not only explain and/or predict chemical phenomena in our material world, but is also used to create new phenomena. For example, the separate disciplines of science and art have come closer together with the advent of new processes and new materials that chemistry has produced. We can now talk of photography as art as well as a chemical process. Painting has embellished itself in a wide array of colourful dyes and paints. Restorations of monuments and other pieces of art rely on chemistry. However, school chemistry has neglected to use the rich, practical chemistry of photography or of paints or of restoration of works of art to situate chemistry in its larger context which may make it personally meaningful to students.

Explorations of such phenomena if addressed at all are relegated to the extracurricular activities of science clubs. If, as Bruner (1990, 1996) claimed, culture gives meaning to action, then perhaps school chemistry education has ignored the larger culture of the discipline of chemistry at the cost of stagnating its own culture, almost to the point of obsolescence and obliteration from students' point of view. It has employed practices and approaches that have changed minimally over the years without recognizing that these practices may be presenting a narrow and limited view of chemistry. The intuitive, generative, practical process orientation of chemistry has largely been overlooked. School chemistry has also excluded students' contribution in its making. How many students have ever published their work in refereed chemistry journals?

Predominantly, the culture of high school chemistry is based on the assumption that learning and teaching chemistry can be divided into discrete elements (student, subject matter topics/concepts, teacher, teaching strategies and tasks, information dissemination, grading, laboratory exercises, assignments, and examinations). The learning and teaching of chemistry consists of problem solving, paper-and-pencil tasks, and very little generative doing. For this approach to learning and teaching to be successful, it must preserve the elements, properties and relations within the pregiven elements and tasks. It thus becomes rigid and rule based. However, for the learning and teaching of chemistry to be meaningful in an ever-evolving world, it requires an open space—a space open for new possibilities and outcomes in both the student and the teacher.

The University and/or College Grip

There currently exists in school chemistry culture what Gold (1992) termed "an obsession with content." The focus and content of school chemistry is voluminous, academic, and geared towards students who are university bound (Fensham's [1984] 20%) and as a result is greatly influenced by university entrance standards. In the early development of the subject, chemistry textbooks were written mostly by university professors. In the later half of the past century there has been a gradual move towards curricula and textbooks that are developed by chemistry teachers; for example, the Nuffield Project developed in the UK in the early 1960s, and the Alchem Project developed in the 1970s and the Nelson Chemistry project of the 1990s, both developed in Canada. However, even with these developments the university influence is pervasive. The Nuffield O and A level school leaving examinations are used in many countries for selection into university. In North America the high school diploma and standardised tests are used for entry into university. Hands-on activities that are essential to understanding chemistry are structured in ways that they can only be performed in the “strange” rooms, the school laboratories, using “strange” equipment and “strange” substances. Instruction about what to do is presented in recipe fashion, leaving little room for student initiative and inquiry. Is it therefore not unexpected that students may develop a compartmentalised view that chemistry explorations and activities are limited to laboratory environments? A promising recent development, the Salter’s Advanced Chemistry developed in the United Kingdom in the early 1990s by the Science Education Group at the University of York in collaboration with teachers, educators, and industrialists, needs to be mentioned. Although still being revised, its focus on modern applications of chemistry and approaches to teaching chemical principles offers an alternative model with which to work in trying to revolutionise school chemistry culture to keep up with our changing world (Holman & Hunt, 2000).

Chemical instrumentation, which is keeping up with the times, can also be intimidating for a student who is not aware that she or he does not need to know the theory and/or mechanics of the instrument to operate it and help in the analysis and chemistry learning. The emphasis put on theories and a step-wise mechanistic view to chemical processes in school chemistry culture leads students to expect that understanding the theory on which an instrument is based is essential to its use. Students engaged in situations demanding experimentation with instruments find it difficult and sometimes frustrating to learn how to use the instruments because the underlying theoretical mastery is lacking.

Attributes of School Chemistry

Contemporary high school chemistry curricula are varied. They range from prescriptive types that stipulate what content, concepts, topics, and hands-on activities should be done and how to do these to the more liberal ones. The latter curricula often comprise a core component and an elective component often offered as modules. They also provide alternate approaches for instruction and have room for both student and teacher input.

Traditionally, chemistry teaching has been more ‘chalk and talk’ with few hands-on activities designed to illustrate, confirm, or verify some aspect of theoretical concepts. Knowledge of students’ learning styles has resulted in a gradual move to incorporate different teaching approaches and activities (see Table 5).

Table 5

Comparison of Traditional and New Practices in High School Chemistry Culture

Practices	Content	Pedagogy	Epistemology
TRADITIONAL Dichotomised teaching and learning activities - learner learns and teacher teaches, knowledge and reality body and mind	Content is universal Fixed/core body of knowledge including facts, theories and techniques Tested, detailed laboratory experiments with known outcomes	Knowledge transmission Information processing, repetition Knowledge is linearly or hierarchically structured Laboratory work is used to confirm/illustrate or support theory	Teacher has all the necessary knowledge and will impart it to the students There is a one to one correspondence between chemical truths and the real world “out there”
	Mathematical component is essential to theory and model building Industrial chemistry, nature of science, philosophy of chemistry and history of chemistry treated as incidental and somewhat trivial illustrations of the societal dimension	Emphasis on paper and pencil mathematical problem solving tasks and drill Understanding can be assessed by written tests and examinations INPUT-OUTPUT model	Student is recipient of the knowledge which she or he can memorise or somehow internalise and reproduce on tests World view is dualistic, there are right and wrong answers that come from authority *(table continues)*

CONTEMPORARY EMERGENT: Informed by new theories of cognition and complexity utilise the reciprocal and recursive nature of teaching - learning processes driven by complex and ecological frames	Knowledge is tentative and diverse - it can be both local and global Theories and models are agreed-upon approximations of the way we understand phenomena Laboratory and other hands on activities can expand and modify the boundaries of the discipline	Both teacher and student educate their awareness to recognise, establish and use rules of the game of chemistry knowing Both participate in the making of history and in the changing of the discipline Teachers and student continually constitute the norms of interactions and the practice	Knowing emerges in interactions and is context-dependent Knowing brings forth worlds of significance to the knower who is inseparable from the knowing Knowing is not a representation of a reality "out there" but a process of making coherences of one's experiences
	Nature of chemistry, history of chemistry, chemistry, technology and society are not add-on to the curriculum but are studied and employed as part of the process of making or modifying the history and nature of chemistry	Both teacher and student are part of the making of the emerging understanding of the history of chemistry	World view is multi-perspectival, principles laws and theories are not "true" but only best agreed upon Knowledge is situation specific and students are part of the context of situations Students create their own knowledge—in the world

One major component whose importance in high school chemistry has been emphasized over the years is problem solving. The conceptualization of problem solving in high school chemistry has been limited to mathematical problem solving. This narrow conception has limited the use of this teaching-learning approach to mostly paper-and-pencil tasks, although it was recognised earlier that problem solving could also be applied in the physical manipulation of objects. Recently there has been a gradual move to understand and redefine problem solving involving manipulation of objects. By refining the goals, understanding the nature of the problem solving, and restructuring it so that it can be used and assessed within the school structure, problem solving is gradually transforming the nature of high school curricula by opening up possibilities for students' input.

With high school chemistry problem solving broadened to include physical manipulation of objects, the structure of laboratory work is also broadening to include the creative aspects of chemistry that have for a long time been neglected. This change has opened up possibilities for different types of interactions and different types of understanding that may be more personal and more long lasting. Students can now be more self-directed and creative in a high school chemistry class.

There is a need to continue to understand student learning processes to be able to open up possibilities for

1. chemistry curricula that are proscriptive and that encourage student input and are accepting of dissent and transformation;
2. teaching methods that are not aimed at preserving the limits of the curriculum or the structure of the discipline but that transform them; enactive approaches that posits teacher also as learner; and
3. problem solving that engages unanswered questions or problems, questions that are intrinsically driven and posed by students.

The reviews of research on science teaching and learning reflect a need for holistic research in which the research focuses on the whole person(s) situated in a context (Gabel, 1994; Levinson, 1994). This research is an attempt to capture the organic complexity that is a feature of learning and cognising and to use that complexity to develop some understanding of the students' meaning making process.

Enculturation or Acculturation

Where is the place of chemistry in the large human culture? School chemistry has a distinct culture of its own, which makes it unique. Although this culture, like all other cultures, is not static, its distinctness over the years has made it gain a special place in the educational, sociopolitical, and economic sphere. For instance, in higher education, students with a good chemistry background, among other requirements, are considered to have foundations to study a wide variety of courses including geology, metallurgy, chemical engineering, pharmacology, pharmacy, biochemistry, and chemistry. Students who leave school with a good high school chemistry background (along with other courses) not only have a good chance to enter university, but can also get a job much more easily in many countries where learning on the job is still a common practice. Chemistry permeates all aspects of our lives; hence the need to make it relevant to everyday living and to make it accessible to everyone. The materials that make up our biophysical environment—that is, the things of which our body is made up, the things we wear, eat, drink, build with, use as physiological remedies—all are chemicals. The fact that for many people high school chemistry is the last formal course in chemistry they will ever take creates an urgent need to develop a course that can help people deal with chemical phenomena they will encounter in their day-to-day living. These may include sociopolitical decisions about the chemical industry, health, and the environment.

The evolution of school chemistry is clearly based on logic and rationality, as are many other disciplines. Certain aspects of chemistry are better taught before others; there is a logical progression. For instance, the teaching of subatomic chemistry radioactivity and alpha, beta, and gamma rays before students are taught about substances, chemical changes, or electrical properties of substances is meaningless and can lead to rote learning without having much significance for the learner. This therefore requires school chemistry to be structured. How the concepts behind that structure are made accessible to students requires that both the teacher and the student be immersed in the culture to be able to understand the nuances, the implicit and explicit features of both the processes and products of chemistry knowledge creation. School chemistry has been able to create some explanations (often simplified) and make some predictions involving phenomena not readily accessible to students in everyday experience that could be tested and verified by other people. It is the success of these predictions and explanations and the creative and sometimes destructive nature of chemistry that make it distinct. The language and the tools of chemistry likewise have developed beyond everyday experience. Gaining access to chemistry, or as Rosser (1995) said, to its mini-cultures, requires a process of enculturation in which one not only learns the language, the techniques, the professional behaviour, and the values, but also learns how to do things with chemistry. An appreciation for and understanding of chemistry emerges from interactions with chemical phenomena and events.

Apart from the chemical "facts," the procedures, and representation techniques, beginners in chemistry also have to adopt a code of conduct to belong. Learning chemistry emerges as acquiring a right of passage into this strictly controlled culture. This is exemplified in the research that uses *apprenticeship* and *enculturation* as metaphors. Chemistry teaching-learning is made more complex by the oversimplified analogies and models employed in introducing concepts. The atomic structure models often presented to beginning chemistry students are an example. Students often leave school believing that atoms are solid spheres with concentric inner spheres or shells containing electrons orbiting in fixed paths and a dense inner nucleus, much like the solar system. Students are never made aware that this is just one model constructed to explain some observations, and that this model has its limitations. To many, this is a fact. At another level students may leave school thinking that atoms have properties that the macroscopic substances with which we deal in everyday life have. For instance, students think that atoms melt or smell or are coloured like the macroscopic substance that they comprise. In the teaching-learning of chemistry an appreciation and understanding of the culture of chemistry is essential for success. How do learners come to develop an appreciation for and understanding of the culture of chemistry? What does it mean for the learner to know chemistry? Does this appreciation and understanding call for a debunking or abandonment of one's culture?

Distinctions or Classifications in Chemistry and Chemistry Education

A Multiperspective View of Knowing

Learning as a process of living mediated by the structural coupling of entities is not limited by our boundaries. We are distinct because we distinguish or make distinctions. Living, learning, and meaning making go on in spite of or with our distinctions. The existing boundaries in learning—for example, boundaries between disciplines such as art, humanities, and science—are boundaries created by human beings to try to organise and delimit their ideas and to recognise patterns or regularities. These boundaries tend to reflect, in their nature, an existing but restrictive dual world view of reality.

Chemistry is a subject in which classifications are made at various levels. Distinctions are made between organic, inorganic, and analytical chemistry. We also talk of empirical and theoretical chemistry. As well, there is descriptive and synthetic chemistry at another level. We describe matter at three distinct levels, of which two are not accessible in everyday living. We describe matter at the macroscopic or bulk level where we observe melting points, smell, colour, and even chemical changes. We also describe matter at the molecular and atomic level as well as at the electronic and nuclear (subatomic) level. The introduction of STS into the chemistry curriculum also adds another dimension to the classification that can be made in chemistry; for example, ethical, legal, economic, and other perspectives. Therefore there is a need for a framework of knowing and learning that is broad and flexible enough to encompass the multidimensionality of human existence. When someone with the authority of a teacher, say, describes the world and you are not in it, there is a moment of psychic disequilibrium, as if you looked into a mirror and saw nothing (Rich 1993).

The question of being addressed, being recognized, feeling addressed, and feeling recognized has to do with how learners and teachers interact and how they view and interpret life. The feminist critique of science raises the question because research shows that science does not address the majority of the learners (Keller 1985; Rosser 1990, 1995; Roychoudhury et al., 1996; Tobias, 1994). This critique not only recognises gender biases and power politics, but also cultural biases. The cry to develop a gender-inclusive science can also be recognized as a cry to include all whose experiences are not recognized by the current practices in science classes.

Pedagogy and Conscious Awareness

If chemistry learning in its introductory phase can be compared with learning a new language, it is reasonable to echo Bruner (1990) and suggest that chemistry

> is acquired not in the role of spectator but through use. Being **exposed** to a flow *of* [*chemistry and chemical*] language is not nearly as important as using it in the midst of **doing**. Learning a language [chemistry] is learning how to do things [*with chemistry*]. (p. 70)

Teachers, educators, and parents have a pedagogic commitment in the sense that they are called upon to interact, make decisions, and set up occasions in which young learners are addressed and feel addressed. This calling demands that the addressor or practitioner know and act appropriately to create a space beside him or her within which the learner can also interact, language, and expand his or her cognitive domain.

Address is an issue of concern in this research because it is the point of contact in the dialogic enactive settings. It can be looked at from different viewpoints, including person to person as in student-teacher, student-researcher/resource person, student-student, or person and setting or context. Students in classroom settings act, change, and respond to address differently because for the most part their learning chemistry depends on the teacher's leading or guiding. The teacher has to invite the students to recognise or see things and events differently. This involves shifting their attention to include particulars that they may not have recognised and to help them realise that they can make sense of those experiences in a systematic and methodical way that is acceptable to the scientific community.

The students' interpretation of the address or invitation and the response thereof depend on the history of the relations that have emerged among all participants and on the setting. The addressor's knowing and acting appropriately at the moment are greatly determined by the context within which the interaction takes place, the structure and history of all participants, the nature of the issue addressed, and by the lenses through which both the addressor and the addressed view the issue at hand. In a sense, address might be likened to a node or a bifurcation point in complex systems because it sets the stage for enactions of multiple understandings. In other words, it is one of the nodes in the network of interactions where possibilities emerge. The responses that students give when addressed by someone or by a situation reflect the ways in which the students understood the address. The action of an addressor does not cause a response. In the case where a student is asked a question in class, for instance, it is not a simple decoding of the words or phrases of the question. The question triggers a series of complex interpretive activity in the addressee that involves the addressee as a whole biological, social, and cultural being with physical, psychological, emotional, and spiritual dimension to his or her existence, resulting in a response that is a reflection of how the addressee relates or sees the relationship of the addressor or the addressor's prompt to the addressee's reality. The response is a reflection of coherences made by the addressee within that context. In the classroom it demands that the teacher as the leading addressor or guide create an occasion for the student to feel addressed and recognized through the interactions and likewise for the learner to choose to address the situation. In other words, this pedagogic commitment calls for mindfulness to the atmosphere/climate, action-thought-language processes, and decisions taken moment by moment. It requires that all participants live consciously, constantly educating their awareness and acting in love towards one another.

How, as a researcher, I choose to address the teachers and students determines how they respond to me. How teachers address the students and how students address the teachers also plays an important role. The students must also feel addressed by the setting to be able to take the risk of enacting their understandings. The students, in enacting their understandings, are taking risks because their knowing is about them; it is part of them, part of their identity. This shows in a simplified way the complex and nonlinear nature of learning, teaching, and cognising. As a way of being in the world, learning emerges alongside an emerging sense of self or selves. When I take a risk and enact my understanding, I am in fact changing my being in the world; I re-create myself.

> A crucial point is that obligation exists only in the discursive universe: it concerns the addressee, the figure created by the discourse itself, not the empirical learner. The discourse does not address a given individual, it creates the place of the addressee by itself and it is up to the receiver to recognise his/herself in this place. (Salecl, 1994, p. 3232)

To more fully address chemistry and to develop some meaningful understanding of it, for instance, the student has to be able to recognise and acknowledge three important factors: first, what its place in his or her life is; second, that it exists both in experience and in the symbolic realm; and finally, that circularity exists between experience and symbolism. Students must be able to recognise and generate for themselves the connections between the symbolic chemical talk and their experiences in learning situations in and out of class for them to have some understanding of chemistry. To be able to operate in that symbolic order, they have to be able to deal with their sense of self as knowers, with a "trained eye" to recognize the patterns and feel the rhythms that chemists ascribe to matter and to chemical events. In other words, they should feel some ownership of their experiences and the ensuing interpretations of these experiences that emerge from feeling affirmed or recognised as a knower within a community. It is that affirmation or nonaffirmation by someone of authority (authority defined by experience in the field) that is part of the address. Address in this case implies a listening to and a listening for the other. It therefore should acknowledge and celebrate difference, dissent, and diverse histories and backgrounds, and embraces possibility.

PART TWO

CHAPTER FIVE

THE RESEARCH JOURNEY

Tradition in science and science education research would have me outline this part of the dissertation in clear distinct methodological steps similar to the laboratory manuals often used for high school chemistry hands-on activities so it is easy to follow and, perhaps repeat. The accounts of the research processes and methods provided here are retroactive and therefore may sometimes sound as though they were all carefully thought out and pre-planned. However, as Simmt (2000) elaborates in her doctoral thesis regarding this type of research, the research process is in itself complex and often not easy to duplicate. As with all human interactions, it is co-emergent and is dependent on the context and history of all the participants. Using one of the models of complexity and chaos theory, she describes the research process as fractal as she described the self-similar "research-in-action" cycles embedded in the process. I have chosen to describe this part of the research as a journey, itself embedded within the longer journey of the entire research process which too is embedded within the even longer journey of living and cognition, trying to make coherent for myself my experiences of living. The striking feature of this journey, within a journey, within yet another journey is the self-similarity observed in all.

Apart from the fact that I am the one journeying, I also find as is the case with the journey of life, I have to create my path in walking. Along the way on this journey I have found energy rich matter that I have chosen to use, in the works of many who have come before me (Maturana 1988; Maturana, Varela 1991; Varela, Thompson, Rosch 1991; Simmt 2000). I have also interacted with many other people including my supervisors, the teachers I have worked with, other professors, high school students and graduate students who in many ways are implicated in this research as they offered me triggers and perturbations that have helped me make sense of the experiences I have had and continue to have on this journey. Bearing this in mind, the description of this journey will in no way be exhaustive nor can it be said to be the only one as I select from a long evolutionary history snippets of interactions that I will focus on in the portrayal of my research design. The research started with questions that evolved from my experiences as both a chemistry student and a chemistry teacher. I experienced difficulties learning chemistry at all levels of my schooling and when I studied for my master of education my research revealed that students still had serious difficulties learning chemistry. Rather than look at the subject or the teaching or the student in isolation I chose to focus on the learning process and decided to investigate that part of the process that I could possibly access in its naturalistic setting, the chemistry classroom. I chose the learning process as it is the focal point of education involving the learner who often is the student, the teacher, the phenomena being studied and the context in which learning takes place. I, however, did not lose sight of the fact that behind the scene both the teacher and I, the researcher, were also learners, learning from each other and also from the students we interacted with.

Exploring this landscape the way I did is a new way of trying to explain and make sense of this natural phenomenon. In addition this research focused on explaining and understanding human behaviour which is unpredictable. As a result the design of the study evolved with the research. The question from which I based the study did not specify method however, a more comprehensive understanding, that captures multiple view points, was developed from investigating the phenomenon with as many tools as possible. Therefore a variety of data collection methods was used including observation, field notes, audio and video taping, class discussions, individual and/or group interviews, and sample copies of student written work.

Collecting Research Information

Advances in technology have greatly increased the number and variety of data collection tools and techniques. In this research, qualitative methods of data collection were used. They combined observation and video-taping of students engaged in activities with interviews and class discussions about instances designed to explore the meanings these experiences held for students. A variety of tools proved to be quite effective.

In addition to observing, video and audio-taping, I kept field notes documenting periodically my own experiences and my interpretations of them and occasionally making copies of students' written materials involving their explanation of various chemical systems. The data collected for this research involved students from: (1) one regular Alberta grade twelve high school chemistry (Chemistry 30) classroom which incorporated small group laboratory hands-on student activity, (2) two grade twelve IB high school chemistry (Chemistry 30 IB) classes which incorporated small group laboratory hands-on student activity. The table below presents a summary of data collected.

Table 6

Sources of Data Collected

Classroom observation	Video	Student working papers	Students' lab reports	Interviews
Iodine clock [3 classes]	30 groups (5 groups)	15 students (6 students)	60 students (2)	15 students (8)
Pop can cell [3 classes]	28 groups (5 groups)	0	48 students (2)	13 students (3)
Electroplating [3 classes]	20 groups (3 groups)	8 students (1 student)	10 students (1)	15 students (5 students)

Numbers used in this report ( )   Total number of classes [ ]

For the analysis in this study I had to select what data to use and how much of the data I would use.

Decisions about the nature of instructional and laboratory activities were made collaboratively by the teacher, myself and my research supervisor. Regular meetings and interviews were also held with the teacher involved.

Observation

I interacted with students in their classrooms as early in the term as possible. The initial classroom visitations were designed for me to start building relationship with students prior to the start of classroom observations in open-entry investigations. Often the first open-entry investigation was conducted within the first eight weeks of the course. During the investigations the teacher and I walked among students observing individual groups as they interacted in the investigations. I observed students as a participant observer. I therefore sometimes intervened if invited to or when I sensed a need to intervene. Other times I would intervene to get a sense of where students were going with their investigations.

Field Notes

During our observations, we interacted with students and video taped these interactions. I made mental notes which I later recorded in my field notes after the laboratory session. Often the field notes were about interesting events that I either did not record/videotape or that had special significance for me that I felt needed emphasising or amplifying. There were often notes about context for instance noting students' absences or express desires not to be video taped on a particular day. This rarely occurred and when it did students still interacted with us and those interactions were audio-taped. In those instances I made elaborate notes about the interactions.

The field notes were also used to record some of my own immediate reflections on the interactions. These highlighted my own interactions, the teacher's interactions, our brief discussions about the interactions.

Audiotaping and Videotaping

To be able to capture more groups at the same time two 8mm video cameras were used. The 8 mm video camera was small, less intrusive and less cumbersome that it allowed us to work beside students. The audio and videotaping were designed to capture individual and group interactions with physical phenomena in the laboratory. Therefore we tended to focus the cameras on the manipulations. The teacher and I were able to capture both the physical and verbal activity including sometimes some of the immediate written work. This also allowed us to capture some of the textured nature of the context where nuanced activity, be it body language, speech or physical action, was not lost completely, allowing us to read more into the interactions.

In this research, having access to two cameras added a different and valuable dimension to the research because we captured different versions of the learning activity. It is possible, for instance, to compare interactions and relations when either one of us worked with various groups. One camera was used during the end of course interviews.

Sometimes students indicated they were uncomfortable with being videotaped but did not mind the audio-taping. In those instances the camera was faced away from students but left on to record the verbal interactions.

For the interviews at the end of the course I prepared several video clips that focussed on individual students or individual groups of students as they interacted in all the open-entry investigations. These video clips were prepared from the different video recordings from both video cameras used. I restricted these clips to between 7 to 10 minutes. I offered them at the beginning of the interview as prompts to jog students' minds and remind them of some of their interactions in the activities. The interviews were video-taped as well.

Class Discussions

There were two kinds of class discussion: pre-lab and post-lab. Students normally had classes/lectures in the classroom. A few days prior to an open-entry investigation the teacher would inform students about it and give them hand outs. Sometimes there would be a brief discussion about the investigation. Most often a more elaborate pre-discussion was held on the day of the investigation before students started the physical manipulations. These pre-lab talks were designed to focus students on technical aspects of the investigation for instance where to get materials, how to set up circuits and a brief description of how instruments worked. After each laboratory session, class discussions about the activity were conducted. In these the teacher, students and researcher talked about their experiences. They also talked about writing laboratory reports. The class discussions were mostly video-taped with the camera at the back of the class so as not to reveal students faces.

Individual or Group Interview

Two types of interview were conducted with some of the students. The first type conducted in the laboratory was brief and it was done immediately after students completed their activity. These were designed to get immediate feedback about how students felt.

The second type of interview was longer and was conducted after the chemistry course was completed. This was conducted in a setting where students could watch a video-clip of their interactions and comment about them. The purpose was to get students to reflect and give an overview of the entire process. The participants were observed and if they permitted, the conversations were video-taped. The videos from these interviews were transcribed and used to explore ways of portraying how students developed useful and effective ways of thinking about chemical phenomena and about their own meaning making.

Sample Copies of Student Written Work

Students were requested at different times to submit copies of their written work. This included pre-lab notes, reflective notes and written laboratory reports. The different data were used for triangulation of results.

Research Sites

This research started by exploring several research sites in the fall term of 1996. A decision was made to stay with one school because it was more accessible to me and it offered a variety of possible research routes. The researcher's interest in fully embodied knowing (cognition) and how students make meaning in high school chemistry situations influenced to a great extent our decision to explore classes that involved hands-on activities. The researcher decided to study students' meaning making processes in their natural setting and that the focus of the research would be on sections of the high school program that would normally be taught. The only intervention made was to modify the activities to allow for more student decision making.

Table 7 describes the open-entry activities conducted. The first three were conducted in the laboratory and were used as my research site. This summary describes how these laboratory activities can be used in different ways comparing the approaches to the labs and the objectives. The handout for the three laboratory activities used in this research are provide in Appendix A and two traditional versions of the iodine clock are provided in appendix C.

Table 7

Open-Entry Investigations

Approach Activity	Step-by-step approach	Teaching objectives	Open-entry	Possible teaching objectives
Iodine Clock Reaction	To illustrate effect of: - temperature - concentration on reaction rates	To confirm concepts already taught to illustrate the different types of variables: - controlled - manipulated - dependent	Technological investigation - how do chemists come to understand complex phenomena?	To find ways to control the behaviour of a reaction To engage in naturalistic scientific investigation including learning how to make decisions, judgements and taking action to explore the nature of science to engage students in the making of science by solving student posed problems
Pop-can cell	To prepare electrochemical cells of different emf.	To demonstrate the energy from chemical reactions can be tapped as electric energy to demonstrate the different chemicals produce different "amounts" of energy	Technological exploration - how can we make a working cell? - how can we judge the utility, efficiency and quality of the cells - is it economic?	To engage students as knowers To find out how to make a cell To learn how to develop criteria To explore and learn about STS and nature of science issues
Electroplating	demonstrate concepts learned in class	To confirm and consolidate concepts learned on electrochemical energy in redox reactions	Exploration of process - qualitative study Product quality Marketability - quantitative study how much product form how much material	To develop procedures that work To establish which one are effective and efficient To explore and engage in STS issues To appreciate the social dimension of chemistry decision making
River project	To learn specific skills in the use of testing equipment	skill training	Complex interdisciplinary exploration of unknown phenomena	To find out what is knowable about the river To find ways of accessing these knowable aspects of the river To determine which ways of measuring these aspect of the river are reliable, and efficient

During the winter term we started working with students on a series of three hands-on open-entry activities that we selected with the classroom teacher. Although we started with one Chemistry 20 class (with twenty-six students) and Chemistry 30 class (with thirty students), we ended up working only with the Chemistry 30 class for the complete term's study due to scheduling difficulties. Of the thirty students, six declined to be video-taped although from time to time they invited us to work with them at their work stations.

During the following academic year 1997/1998, we continued the research with two full year Chemistry 30 IB classes that the collaborating teacher taught. All the students in both classes agreed to work with us and to be video-taped. In one class there were twenty-eight students while the other had twenty. With this group a fourth activity, the river project, was added. The river project was selected to fulfill the requirements of the Chemistry 30 IB program.

Data Analysis

Analysis of data was carried out continuously as the research evolved and emergent questions addressed. The biggest challenge was how to take the complex and rich data collected on video and to turn it into text that will certainly eliminate or cover up the complexity of the processes investigated. With the large volumes of data collected, what do I select, how do I select, how do I represent what I have selected? Would my portrayals still retain some of the complexity encountered? The reasonable thing to do was to start writing and find people who could give me feedback on my portrayals and interpretations.

Because of the two cameras used I always immediately reviewed the 8mm tapes and dubbed them onto a VHS video. This I found useful because the 8mm videos always served as backup copies, the dubbing onto the VHS gave me a chance to view both recording immediately to help me learn from the videos what to improve in my researching skills. I could identify what line of questioning invited students to work with me or not. The third use for this strategy was that I could view the VHS as many times as I could. The initial dubbed tapes contained two versions of each laboratory session. After viewing this video two or three times and combining that with my own fields notes and memory of class interactions I selected groups that I thought were interesting. At first I identified for each class and each session about 6 to 8 groups to focus on. I would then create video-clips of each group combining the teacher's version and my version in the same video-clip. Then I transcribed the videos. These transcripts were then used along with the video-clips to analyse and interpret the data. I selected and transcribed all the video clips. A similar technique was used to develop transcripts for the end of course interviews although only one camera was used this time.

For analysis, various approaches were used including transcribing verbal utterances from all the selected student video clips, and interviews as well as interviews and discussions with the teacher, the student teacher and other resource persons. Students' reflective notes, analysis and evaluation part of the laboratory report were analysed for themes based on how frequent students said or did something. Some themes emerged out of action but they were nuanced in the sense that most times it was the hesitant look, the hesitant action the frequent asking of the same question that pointed to a theme. From these initial interpretations I wrote papers or simply made presentations to various audiences, discussed with other researchers and graduate students. Part of the analysis also involved writing and presenting working papers at conferences from which I got feedback about the research and about the learning process. All the presentations made involved using transcript and video-clips.

Following the data collection period I took a full year phenomenology course in which part of the requirement was to do phenomenological writing about lived experience. I used this as an opportunity to analyse and interpret some of the data collected on video. As this was a graduate writing course where we often presented and discussed our writing to the class, I presented the class with some of my writing, shared a video clip of some of my research and used this as a chance to do further analysis and interpretation from the feedback I received in those sessions. Other opportunities emerged where I could explore more analysis in a group setting with a different set of graduate students. In one, I attended for two semesters a weekly teacher education research seminar where participants presented and discussed research issues of their interest. The majority of regular participants were graduate students and professors in elementary education who had a lot of teaching experience and were all at different stages of their own research. I presented part of my research vis a vis some video clips, transcripts and my accounts and interpretation of the research. The third opportunity was a graduate course offered in spring focusing on the discipline of noticing. The student group was larger and more diverse including graduate students in mathematics education, science education, English education, pharmacy, elementary education. Valuable feedback was obtained from all that helped me further my analysis. In addition to this I also shared some of my work with colleagues in our yearly doctoral cognition group. Their contributions regarding the research and other aspects of cognition helped me fine tune my approaches to the interpretation, analysis and representation of the research findings.

Students' written work was mainly used to illustrate and corroborate some of the ideas that emerged from the analysis. Quite striking and somewhat telling were the reflective notes. These were often presented as part of the transcript during the presentations.

Participant Researcher

In this research, since I was not the classroom teacher, my role was defined by my perceived needs of the student(s), the teacher(s) and myself. I was not only a participant researcher but also a resource person, interacting with students during their activities, providing materials when necessary, discussing with them and helping them formulate their ideas about the understanding of the activities and assisting them in reconciling their ideas with those used by chemists. My participation as researcher and resource person, however, created for me dilemmas in terms of my acting in the moment. As I recollect some of my early visits, the visits were filled with mixed emotions. I was glad I could start making contact with students but was too cautious not to sound like an expert in their territory although they wanted to know my education background. They sounded impressed by my credentials and the non-threatening position I adopted while working with them. Initially, I was somewhat hesitant not knowing how far the classroom teacher expected me to go. It turned out to be a very welcoming experience.

Students' expectation of me included being able to give them answers, recommendations and help in determining how to set-up their "experiments" or solve emergent problems. However, the research design put more emphasis towards projecting students' original ideas and actions. The situation involving Bob, who incidentally had declined being video-taped, is a classic example. In this activity, Bob and his partner were doing the iodine clock reaction activity. Although Bob was present during the pre-lab exercise the previous day, he did not seem to have understood the objective of the exercise. His partner was absent during the pre-lab activity. After a few minutes of reading the handout, and putting on the protective gear, Bob called on me for help. In his quick reading, Bob interpreted the goal of the exercise as stopping the reaction at 20 seconds not realising that they had to figure out a way of making the reaction go to completion in 20 seconds. So using his ideas, and my prompting questions we discussed what the results of such an exploration would teach us and ended up realizing that the question asked by the activity was different. On the other hand, students who felt that they had no need of my assistance at times were less open to my coming into their territory.

In general, students' engagements with me were not the same as with their classroom teacher. In trying to capture this interesting phenomenon, we decided to have two cameras in the lab, with the classroom teacher working with the second camera. A qualitative comparison was made regarding the type of questions students asked each one of us and the type of intervention we each provided.

Proponents of observation as a research tool suggest that

> as an outsider an observer will notice things which may lead to understanding the context. The participant observer gets to see things first hand and to use his or her own knowledge and expertise in interpreting what is observed. ... Observation is the best technique to use when an activity, event or situation can be observed first hand, when fresh perspective is desired, or when participants are not able or willing to discuss the topic under study (Merriam 1988, p. 88-89).

Although being a participant observer has a high potential for informing the study since it situates the observer in the setting, it is also problematic. In a class setting, for instance, issues of trust, confidentiality and intrusion have to be dealt with since the researcher or participant observer is actually encroaching on students' territory. In almost all cases, students have to be willing to invite you in to their microcosm or turf. Students may not always be willing to invite you in.

Research Ethics

Written consent was obtained from all students and teachers to video and audio tape and to collect samples of their written work where appropriate. The students were made aware that their participation was voluntary and that they could opt to participate or not to participate at any moment they chose to by either informing the teacher, the student teacher or any of the researchers in class.

An effort was made to recognise and respect the students' comfort level with being video taped so that when I sensed that a particular group or student was not comfortable, I turned my attention elsewhere although in some cases this proved difficult because the students invited me into their activity as a resource person and not a researcher. In such cases only the audio tape was used and the students were made aware of this. Sample written work was photocopied from ungraded originals submitted as assignments. In some cases copies of the rough work was requested and copied.

Ethical considerations in the interpretation of the data included consulting with, and interviewing the classroom teachers about the events and their interpretation. The descriptive accounts of the engagements were submitted to the teacher and the teacher was asked to assess the validity and accuracy of the accounts and to comment on the interpretations.

Class discussions of the activities carried out were video taped with the camera set at the back of the class so as not to capture faces and reveal students' identity. Small group discussions and/or individual interviews were set as short as the students were comfortable since it was difficult to set longer time slots out of school time due to students' commitments. Most of the longer interviews were set at the end of the school term where students could review video clips of the activities and comment about their overall experiences. These were also video-taped with the students' permission.

To ensure anonymity, the names of students and teachers were changed in all the accounts and portrayals. The following names are used in this study for the following people:

Dr. Muelenberg is the classroom teacher

Mrs. Smith was the student teacher

Cees, Manuela, Viet, Jason, Ubbo, Peter, Rami, Alex, Jager and John were all male students

Saskia, Maureen, Veronica, Paula, Terrilyn, Priscilla, Kim, Meg, Ursula, Salome, Joanna, Kate, Liz, Becky, May and Irene were all female students

Interpretation and Representation

In describing students' experiences great effort was made to use as far as possible students' own words. Interpretations and explanations were derived from an understanding of enactivist ideas. In this research endeavour, who is doing the talking? Who am I talking about? Do I really know the students' experiences? How do I represent the richness and multiple voices or perspectives of their experiences, reflections and enactions? What criteria do I use to select what to represent as experience? These are issues that I had to reflect on and question in the writing of this dissertation. I have tried to keep them visible so that the reader and I do not forget that I am the one writing and in writing I bring forth myself, and my understanding of myself and my world.

Preparation for the Investigations

The open-entry laboratory activities done by students were chosen by the teacher in collaboration with the researcher from a number of activities found in the textbook in use.[6] The sessions were scheduled during regular class time in the Chemistry 30 laboratory. Students worked in pairs on an activity. In the pre-lab talk, the teacher sometimes demonstrated and elaborated on some difficult technical detail such as setting up circuits and using some instruments. Students were always informed ahead of time, provided with handouts (Appendix A) and asked to think about their design for the investigation and also to determine how they were going to record their results.

These open-entry investigations were conceptually structured so that we could start with any one of them independently. We ended up carrying them out as a series dictated by the order of the topics in the school curriculum and in the textbook, starting with the iodine clock reaction, as early in the course as possible, followed by the pop-can cell activity midway and, later in the year, the electroplating activity. For the two Chemistry 30 IB classes, students conducted a fourth open-entry type of long-term activity, the Group 4 (River) Project, as it was called.

For this dissertation, the interpretive accounts presented are from a total of 10 groups of students selected from the three classes. The accounts highlight different aspects or stages of students' meaning-making processes. A brief description of the different investigations is provided separately, starting with the iodine clock reaction activity. A brief commentary of my interpretation is also offered after each account that highlights the enactivist understanding of the experiences.

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[6] In typical classes teachers variably chose to do these activities or not.

CHAPTER SIX

ENACTING "VARIABLE" WITH THE IODINE CLOCK INVESTIGATION

> Meaning includes patterns of embodied experience and preconceptual structures of our sensibility (i.e., our mode of perception, or orienting ourselves, and of interacting with other objects, events, or persons). These embodied patterns do not remain private or peculiar to the person who experiences them. Our community helps us interpret and codify many of our felt patterns. They become shared cultural modes of experience and help to determine the nature of our meaningful, coherent understanding of our "world." (Johnson, 1987, p. 14)

Classrooms are complex learning-teaching environments. Complexity here does not only arise from the complicated subject matter to be taught and learned, the various curricula goals, the various learning styles, and the different teaching strategies, but it also arises from the action-thought processes involved in making meaning. As Johnson (1987) stated in the above quotation, not only do meanings emerge out of our embodied experience and perceptions, but they also emerge from our culture—a culture which inherently also depends on our shared meanings. According to Bruner (1990), "Our culturally adapted way of life depends upon shared meanings and shared concepts and depends as well upon shared modes of discourse for negotiating differences in meaning and interpretation" (p. 13). There is endless circularity between culture and meaning making; for instance, classroom practices may explicitly or implicitly convey a certain image of science (Desautels, 1998) that can become an accepted cultural way of viewing science.

In traditional school laboratory situations, where the laboratory activity is used to confirm or verify concepts, students are provided with well defined problem situations, detailed procedures to follow, materials and equipments selections are made and often present conclusions are presented to them. From these activities, students are expected to seriously make sense of the observations, interpretations and conclusions made and to integrate them with the expository information given in lectures. The processes required of students to do this integration are highly complex. However, the question remains, to what extent are students able to engage and integrate the different components and what kinds of meaning are thus derived? Further, one might wonder, what kind of culture of science (chemistry) does this promote?

On the other hand, the nature of open-entry investigations requires students to seriously engage the activity every step of the way. In open-entry investigations, the level of self-direction and decision making in which students have to engage in offers them a space to immerse themselves in the problem. In this classroom, students become part of the context—their actions form the context and meanings and they serve to form and transform the culture of the classroom. At each step students have to make decisions and justify the decisions to themselves and other members of the classroom community. There is ongoing feedback built into the manipulation of objects as students investigate their problem (Gooding, 1990; Roth, 1998).

Teachers also experience the challenges of the inherent complexity when engaging students in open-entry investigations. They constantly have to absolve themselves of tendencies to direct, to give too much information, to remove the hurdles, and to help students overcome their uncertainty. Through their actions and interactions students and teachers develop new patterns of behaviour that depend on their understanding of the situation and the problem at hand (Rop, 1999, 2003).

In an open, high-activity, hands-on high school chemistry laboratory setting, it is the culture--the practices of chemistry, and those practicing it—who interpret the individually felt and collectively shared patterns. It is the members of the class community who negotiate the criteria of validation of actions, processes, and products and the criteria of acceptance of its own members. They decide in action what counts as success, what counts as an adequate process, what counts as knowing. The complex and layered meanings that emerge from these settings depend on how everyone interacts with each other, with the natural phenomena and with the body of chemistry.

The following accounts are my interpretative reconstructions of some of the students' speech-action-thought processes as they engaged in making meaning of the open-entry investigation called the "Iodine Clock". The challenge of studying human interactions and attempting to make portrayals of these rich and complex phenomena is that portrayals can never be exhaustive and complete. The construction of one portrayal often results in the emergence of new understanding of phenomena, which may allow one to see the phenomenon from a different perspective which could highlight one aspect of the experience over another. Any portrayal is therefore not the whole picture. Keeping this in mind, in this chapter I describe and highlight several selected aspects of students' open-entry investigations: including how the students entered into the investigations; how they negotiated the meaning of what they understood the problem statement to be; how they decided to proceed at each stage; how they negotiated the meaning of their findings, and; what meanings emerged for them as recorded in some of their reports and reflections on their experiences. My accounts will also include how students' use of instrumentation impacted their experiences. After the accounts in a given section, I will present my interpretations from an enactivist perspective of students' interactions in these engagements. The accounts are generally organised to describe the following:

1. Preparation for the investigation, including
    a) the pre-lab talk and the basic description of the objective(s) of the activity
    b) any assignments or instructions given to students to prepare for the activity
    c) clarification of obscure technical detail or use of new instruments
2. Entering the engagement
    a) students' interactions
    b) teacher interactions and interventions, including ensuring that all materials were available, and any on-the-spot need-to-know teacher announcements
    c) researcher's interactions and interventions
3. Concluding the activity
    b) reflective notes or any recorded reflective conversations at the end of the lab
    b) post-lab class discussions
    b) written lab reports and post-lab interviews.

To make reading easier, I established a writing style that will enable the reader to distinguish transcripts and direct descriptions of interactions with students from my own writing about the interactions and about the research. The former are indented. In the transcript, I present myself as the researcher. Transcripts also carry different kinds of information including unfinished phrases, questions, statements, descriptions of gestures and bodily movements which from my view informed and offered triggers in the interactions and the researcher's immediate commentary about the interaction or emphasis. This style is coded in the summary below:

- unfinished statements, questions, or phrases: ---
- researcher's emphasis: [ ]
- researcher's commentary or descriptions of bodily action or positioning: ( )
- missing or omitted parts of a quotation; . . .

Iodine Clock Activity

Most science activities involve manipulation and controlling of variables. For many students, the concept of variable is limited to what is described in the laboratory manual or handout. This is because most science activities are illustrations or verifications of concepts or manipulation of a variable according to a given set of instructions in the laboratory manual or handout.

The iodine clock activity involved a reaction between two colourless solutions that turned dark blue when the reaction is complete. The open-entry activity offered in this class was designed such that students did not have to know the chemical composition of the reactants to do the investigation (see Appendix B for a traditional version with a given procedure). The objective of the investigation was for students to create and test a procedure for making the reaction occur in 20 ± 1 s. When students were confident that they had reached the objective, they were expected to carry out at least one trial for either the teacher or the researcher to confirm their results. To help students develop a clearer description of their procedure, in this replication trial the teacher or the researcher would time the reaction, i.e., use the stopwatch and students had to give clear instructions that they would write as part of their procedure.

From previous (non-open-entry) activities, students had not had the experience of determining and deciding for themselves what a significant manipulated variable was.

They knew that some variables could be manipulated, some could be controlled, and some responded. What that translated into in open-entry activities was yet to be established by the students. In their activities the task for students involved recognising that they had to control reaction parameters and manipulate a chosen one to get the reaction to do what they wanted it to do. Students' decision making also included deciding, for instance, what apparatus to use; when to start and stop timing the reaction; whether to swirl, stir, or shake the reaction mixture and how often to do this, if any at all; and how often they would try out a set of given conditions.

A few days before the lab the teacher informed students that they would perform the iodine clock reaction. They were provided with the hand out (Appendix A), which gives them different information including what the students usually had to focus on. This is indicated on the hand out as check marks beside the particular laboratory activity component. Students were asked to focus on the design and procedure for the activity. They were advised to choose and work with a partner in their preparations.

In the following section, excerpts from four student pair are presented to portray the various entry approaches that students employed. The student paired themselves up voluntarily. The pairs presented are:

- Manuela and Viet (both boys)
- Priscilla and Maureen, (both girls)
- Agasta and Veronica, (both girls)
- Cees and Saskia, (male and female, respectively).

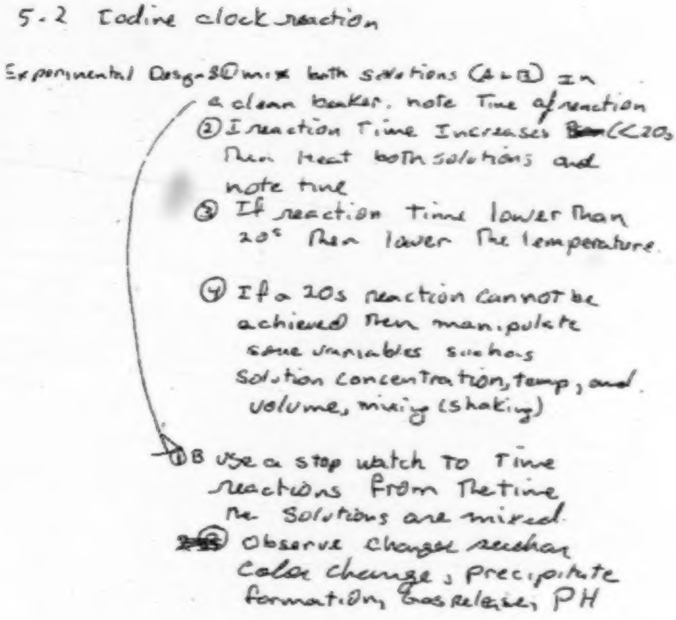
Entering the Investigation

The four stories you are about to read illustrate the ways in which students conceptualised their task and entered into the chemistry activity. Students had prepared for the activity in significantly different ways based upon their understanding of the task. The extent of their preparedness is reflected in the notes they prepared and in the ways they interacted.

Manuela and Viet: Structurally Coupled Interactions

The interactions of this pair of students are presented here to highlight two aspects of their acting in this problem-solving space: that the students had worked together in preparing for the activity, as was reflected in the ways that they wrote their pre-lab notes; and that in working through the investigations, their actions seemed to complement each other, to the extent that they seemed to become a "learning/doing" unit.

Early in the class the researcher approached Manuela and Viet. She found that they had a thermometer; some test tubes; five beakers, one with ice, two with some solution; and a funnel among the things they collected. This was an indication to the researcher that they had thought through the task and had developed a problem-solving strategy for this investigation. It appeared that both students had decided to manipulate the reaction temperature for their investigation. They had talked about it and agreed on a common strategy. The material they had collected, their pre-lab notes (Figures 2 and 3) and their early actions prompted the researcher to ask them about the variable they would be manipulating.



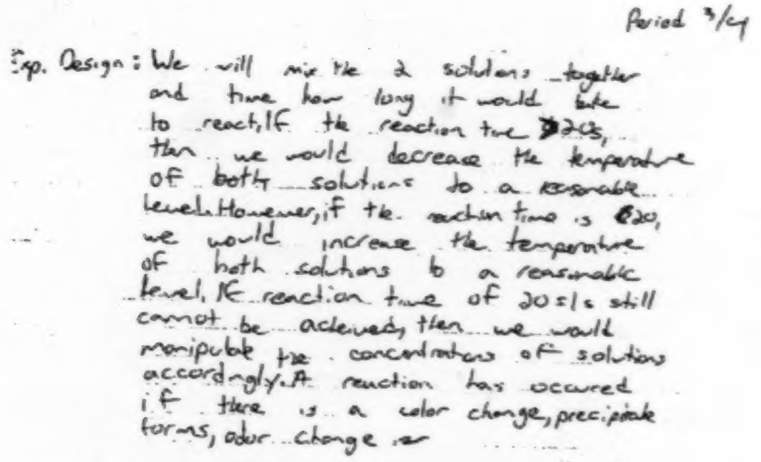
5-2 Iodine clock reaction

Experimental Design ① mix both solutions (A + B) in
a clean beaker, note Time of reaction
② If reaction Time Increases ~~[illegible]~~ ($<$20s)
Then heat both solutions and
note time
③ If reaction time lower than
20s then lower the temperature.

④ If a 20s reaction cannot be
achieved then manipulate
some variables such as
Solution concentration, temp, and
volume, mixing (shaking)

①B use a stop watch to time
reactions from the time
the solutions are mixed.
~~[illegible]~~② Observe changes such as
color change, precipitate
formation, Gas release, PH

Figure 2. Manuela's pre-lab notes.



Period 3/4

Exp. Design: We will mix the 2 solutions together
and time how long it would take
to react, If the reaction time $>$20s,
then we would decrease the temperature
of both solutions to a reasonable
level. However, if the reaction time is $<$20,
we would increase the temperature
of both solutions to a reasonable
level. If reaction time of 20±1s still
cannot be achieved, then we would
manipulate the concentrations of solutions
accordingly. A reaction has occured
if there is a color change, precipitate
forms, odor change or

Figure 3. Viet's pre-lab preparatory notes.

Researcher: What are you thinking of doing? Are you manipulating temperature?

Manuela: Yes.
(Researcher moved to another group as this group continued to prepare for their activity. A few minutes later the teacher approached them and found among their activity a measuring cylinder containing a clear liquid with a thermometer inserted in it.)
Teacher: What are you guys thinking of doing at this moment?
Manuela: We are going to try room temperature. We are reacting them at room temperature to see if the reaction will occur in twenty seconds. Then we will raise the temperature.
Teacher: You are going to raise the temperature?
Manuela: Yes. And if it is too much we will lower the temperature with the ice.
Teacher: Okay. So you are going to try one and then try the other?
Manuela: Yeah. (Then he lifted the thermometer a bit and said to Viet, who was watching and waiting with a pen in hand and a white sheet of paper in front of him). Twenty two!
(Viet pointed to a small beaker beside the measuring cylinder as if to say, "Here, it is ready")
Teacher: Are you feeling certain about which way you are going here? Do you have confidence in trying this?
Manuela: Yeah. (He took out the thermometer and moved as if to insert it into another measuring cylinder with solution, when Viet quickly interrupted).
Viet: No, no, no! (He picked up the wash bottle with distilled water and handed it to Manuela) Wash with this first.
Teacher: What were you thinking there?
Manuela: We are gonna mix it up. I forgot about that (He moved over to the sink and rinsed the thermometer).
Teacher: If you are doing temperature, what do you think you might do at this point? In terms of the problem you just had there? What would be best?
Manuela: (As if, he was thinking aloud). What would be the best? Uhhh. (Paused). We probably might have to do it again.
Teacher: Why don't you ---
Viet: __get another one?

From the incidents described above it is evident that the students used trial and error as their initial entry approach. Having chosen a variable to manipulate, their entry strategy depended on the feedback they obtained from interacting with the materials and the trends they could decipher from their interpretation of the initial findings. For instance, they left the first reaction at room temperature, evaluated the result from that, and then used those results to inform the next step, whether to increase or decrease the reaction temperature. Their discussion with the teacher suggested that their plan of action depended on their perceived and intuitively learned behaviour of natural phenomena as they talked about the direction they intended to follow. “If it [reaction time] is too much, we will lower the temperature with the ice,” said Manuela. Their intentions and actions were tentative. They knew that they could try raising the temperature or lowering it depending on their initial trial.

Another observation that can be made is that one student’s actions influenced the other student’s actions. Manuela’s hand movement with the thermometer towards another measuring cylinder triggered Viet’s interception and subsequent action as he picked up the wash bottle with distilled water to hand it to his partner. This coordination of action was purposeful; and illustrates their meaning making in action. It is also significant that further interaction with the teacher (he asked about putting ice in the test tube) occasioned the students to consider other possibilities regarding their procedure. The teacher did not tell them what to do but offered a prompt that triggered another action in which students had to think about other viable ways of doing.

The concepts of structural coupling and embodied cognition offer us a way of explaining the students’ interactions. Viet’s history of interaction and structural coupling in this high school chemistry laboratory setting made possible a sphere of behavioural possibilities including his quick response to his partner’s actions (moving the thermometer from one solution to another and the prompt the teacher offered. Noticing that his partner could contaminate the other solution, he quickly intercepted Manuela’s action and offered a different way of dealing with that possibility. As the teacher continued to ask them questions, Viet was able to not only to complete the teacher’s question, but also to come up with a question that opened up possibilities for further action. A new element of the procedure (in this case a second thermometer) was introduced in their procedure. In turn, this opened up yet more new possibilities of dealing with contamination and introduced ideas of efficiency; elements that emerged from their history of existence as knowers and as members of this high school chemistry culture as portrayed in the excerpt below:

> Teacher: Go over and see if you can get another thermometer.
> Manuela: That's true.
> (Viet put down the pen and went to the front of the room)
> Teacher: What would that help to do?
> Manuela: Reduce the contamination possibilities.
> Teacher: That's right, and also make the process more --- ?
> Manuela: Faster.
> Teacher: Yeah, efficient, that's right.
> (Manuela put the thermometer down, placed the wash bottle where it was before, moves some of the beakers a little further to create a less cluttered work space in front of him, and Viet returned with a second thermometer)
> Teacher: (addressing Viet) How do you think that is going to help you now, getting another thermometer?
> Viet: It probably won't contaminate.
> Teacher: And also? What else?
> Manuela: (whispered) Efficient.
> Viet: Yeah. It is more efficient. (The teacher left the group as they prepared for their first trial)

The two excerpts show an evolution, where the setting, the participants' histories, the materials, and the interactions co-specified what meanings were made. They were all complicit in the meaning-making process. Students had already come to understand (through other non-open-entry laboratory investigations) that efficiency was a criterion that they could use to measure the success of their procedures. This history informed them as they realized how it would transform their actions. The students continued with their interactions, sometimes with the teacher or the researcher participating with and beside them in their meaning-making processes. With the first few trials completed and a fairly workable procedure that could be used in further tests established the students' trial and error gradually became systematic. From the accumulated results they deciphered patterns or trends that served as feedback informing them of possible subsequent steps to explore.

The interaction recorded in the last five to six lines of the above excerpt exemplify a contribution to students' meaning making emerging from the social culture patterns and norms established in this classroom. Manuela, who had already come to realize that an extra thermometer would increase their efficiency, whispered to Viet, "efficient." Such interactions enhanced their structural coupling as they learned that they can depend on each other:

> Teacher: How are things going since I was around here last?
> Manuela: We have some results.
> Teacher: So, Is the strategy working here?
> Viet: Yeah.
> Manuela: So far.
> Teacher: What are you thinking now in terms of what you are going to do next?
> Manuela: We are going to lower the temperature a little more for A and see what happens.
> Teacher: Lower the temperature of A. Okay. (He left the group briefly. Then he revisited) What is happening here, guys?
> Manuela: We are still trying to lower the temperature, and we are still not there yet.
> Teacher: Yeah. You are changing the temperature of both A and B.
> Manuela: Both, and we are trying to see.
> Teacher: And what was your last result?
> Manuela: Both of them at 10 degrees, and (pointing to the record sheet) we came under fifteen point seven eight.
> Teacher: So what are you trying this time?
> Manuela: We are going to lower it to around five or so and see what we can get with it and proceed from there.
> Teacher: So you were manipulating one variable, manipulating the temperature of A, and now you have switched to changing both A and B.
> Viet and Manuela: Yeah.
> Teacher: To get the temperature of both of them the same.
> Manuela: Yes.

This open-entry task had enough flexibility to allow the students to change their procedure or their materials any time. In the excerpt above, Manuela and Viet had developed a procedure in which they initially cooled one solution only. From the results they obtained, they decided to change strategy and cool both solutions. The decision to cool both solutions was made by the students independently of the teacher's or the researcher's intervention. The researcher, trying to understand their decision to change strategy, asked them a few questions as they continued investigating and negotiating what readings they would accept:

> Researcher: So you are cooling off the solutions before you react them?
>
> Manuela: Five-point-something—let's say five. (Viet wrote down the number as Manuela took out the measuring cylinder from the ice bath, put down the thermometer, and waited. Viet got his solution out of the ice bath; without drying the measuring cylinder or letting the bath water stop dripping, he quickly poured the solution in the beaker in front of him. He then puts the measuring cylinder down and picks up the stopwatch and holds it. At this point I noticed that they seemed to be using the same beaker over and over to mix their solution, washing it after every trial.)
>
> Manuela: Ready, start! (He poured the solution he is holding into the same 250-mL beaker, and Viet pressed the start button on the clock.)
>
> Researcher: While we are waiting for the reaction to proceed, why is it important that you make sure that the two solutions are in ice water before you start? (Viet, who is timing, stretches his arm towards the beaker as if noticing that a change would occur soon and then quickly presses the stop button and shows us the clock.)
>
> Researcher: Mm-hmm! It's getting there.
>
> Manuela: (excited) Just about.
>
> Researcher: Yeah.
>
> Manuela: If we lower it down more --- (He returned the researcher's question) I guess it is important just to make it a lot more efficient—to make sure that they are both at the same temperature before we put them in.
>
> Researcher: Right.
>
> Manuela: Because if one is too hot and the other one is not, it's gonna affect the reaction.
>
> Researcher: And the reaction temperature would be different from the temperature that you have actually measured?
>
> Manuela: Yeah.

This interaction between the researcher and the students is interesting because it illustrates how each person immersed in the activity knew when and how to interject. The researcher, who was interested in finding out why the students had made the procedural decision to cool both solutions in the moment had to recognise where the students' focus was. Delaying her questions and co-focussing with the students on their physical interaction with the reaction allowed the students to complete their trial run uninterrupted. Gestures were frequently used in these interactions. These gestures expressed in many cases, participants' embodied knowing-in-the-moment. When participants were fully immersed in the activity, these nonverbal gestures had meaning that all participants understood. Viet's stretching out his arm just before the solution changed expressed his bodily knowing, his bodily connection with his environment, and his anticipation of what he felt was about to take place. Although this gesture did not answer the question that the researcher had just asked, it momentarily shifted all participants' focus, in a timely fashion, towards the most urgent part of the activity, the endpoint of the reaction. This allowed all participants to witness the reaction mixture change and the accompanying stopping of the stopwatch, a process that would enable participants to accept or not accept the results. Viet, having successfully focused everyone's attention, stretched out his arm confidently towards us to show us the reaction time that he was able to record with the stopwatch. Everyone was in agreement about the results hence the researcher's question could be returned to without interfering with the trial.

Gestures, bodily movements, and positioning were a significant part of meaning making. Viet, who actively participated in this meaning-making process, communicated mostly through gestures. Gestures are an example of bodily expression of embodied and sometimes nonverbal or preverbal knowing. Part of the student's knowing is encoded in the student's bodily movements. Within the context that this knowing is enacted, the gestures and bodily movements have meaning for participants and are complicit in the overall process of meaning making. As will be seen later in this chapter, gestures facilitate the creation of language-in-action.

Different students approached this open-entry activity in different ways. Within groups, individual students had different interpretations of the prompt offered to start the investigation. An example is given in the next portrayal of an all-female pair comprised of Maureen and Priscilla. Starting to investigate for these students meant negotiating what the problem statement as well as a reasonable problem-solving approach could be.

Priscilla and Maureen's Surprise: Stumbling on to a Solution

A different story of entering into scientific meaning making is told in Priscilla and Maureen's interactions. Priscilla and Maureen had worked independently on the pre-lab preparation (see figures 4 and 5). Each student prepared and brought to the class a brief paragraph hand-written on the lab hand-out describing their initial "imagined design of the investigation." This imagined design was based on each student's understanding of what was presented to them as a prompt for this open-entry activity. Watching the two students begin the activity, I was interested to find out how they decided which design they would follow. The following portrayal of their interaction is presented, from the researcher's perspective, as a story where Priscilla narrates how they carried out the investigation.[7]

> When I was given the lab handout, the previous day, I did not realise that I would have to design the experiment and figure out what to use and how to use it by myself. The student teacher, Mrs. Smith, asked us to think about the design and to plan for the activity. All I could think of was to test the solution pH, concentration and temperature. I could use litmus paper --- yes that seemed reasonable. So I wrote down my experimental design.
>
> *A solution A and B is tested with litmus paper to identify and acids or bases, to understand more about the solution. Also a concentration test should be also done. Increasing temperature could increase the reaction of the solution. Changing the volume of solution A.*
>
> The laboratory experience was a nightmare in the beginning since I did not have a clue where to begin. So I played it by ear and watched what others were doing. No one mentioned litmus or pH. What were we supposed to do, I wondered to myself? Our teacher gave us very few instructions: where to get the solutions, approximately how much to get and where to get the stop watches. It was fun trying to figure out how the stop watches worked. No sweat, I said to myself. As I watched other students prepare for the activity and I talked to Maureen, I realised that the activity was more involved. Actually Maureen had a different interpretation of what we were supposed to do. So after spending sometime talking while we cleaned the glassware I agreed that we try Maureen's approach. This is part of what Maureen had written for the lab preparation:
> *As a control, equal amounts of solution A and B are reacted with each other and a time recorded. A manipulation of volume in solution A will be changed to have the reaction between 20 ± 1s --- Add 5mL of each solution and record time.*
>
> We decided to carry out the reaction in a beaker using the amounts Maureen had suggested we start with, that is five millilitres, and were very lucky to get 20.39 s in our first trial. We did not realise that we had actually found the answer to the problem. So since we had decided to change volume of solution A, we did a second trial with 4mL of A and 5mL of B and the time we obtained was 18.27 s which was less than the target reaction time. So we repeated the first trial and still the time was 20.41 s. We thought we were doing something wrong so we reduced the volume of both solutions, using equal amounts of solutions we made two more trials and the results were consistent. We then decided to call the teacher because no matter what we did we were getting the same results, something had to be

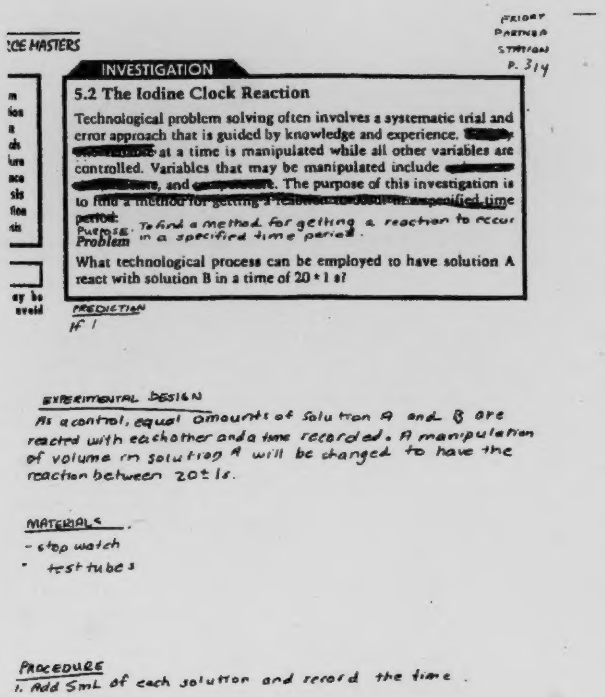
---

[7] This narrative device is purposefully being employed to try to invoke the voice of the student. Although the pair's utterances are taken from the transcripts and there written work and reflections, it is I the author who wrote the narrative and imbued meaning into their utterances and actions.

> wrong. To our relief, we had done nothing wrong. When we tried the activity with the teacher to verify our results, we obtained the same results as before. It was hard to believe that we were done. We gladly cleaned our glassware put everything away and waited for the class to end. Our lab report will be straight forward, I thought to myself.

In contrast to Manuela and Viet who had conceptualised the experimental design very similarly to each other, Priscilla and Maureen's pre-lab notes reflect that they had conceptualised the potential investigation design in different ways. Looking at Maureen's notes, one can recognize that her investigation is about chemistry, as she talked about testing acidity and concentrations of solutions. However her focus seemed to hinge not on the process of making a procedure to solve the problem posed but to find the identity of the solutions. This perhaps arose from what she knows about chemistry; that solutions could be either be acidic, basic or neutral. Knowing this could perhaps help her find ways of working with the problem. On the other hand Priscilla's notes suggest that she thought of process as being part of chemistry doing. Therefore one could investigate processes or procedures.

In their negotiation of the problem and an entry strategy it is possible that both students were influenced by watching what other students were doing. In that sense, they used their colleagues' interactions to evaluate their own strategies and to choose one. Their handling of the results also speaks to their problem solving. Although they had unknowingly developed a workable procedure for solving the problem and had run a number of successful trials, it seems as though they still did not know what the problem



:CE MASTERS

FRIDAY
PARTNER
STATION
P. 314

INVESTIGATION

5.2 The Iodine Clock Reaction

Technological problem solving often involves a systematic trial and error approach that is guided by knowledge and experience. [redacted] at a time is manipulated while all other variables are controlled. Variables that may be manipulated include [redacted], and [redacted]. The purpose of this investigation is to ~~find a method for getting a [illegible] specified time period:~~

Purpose. To find a method for getting a reaction to occur in a specified time period.

Problem

What technological process can be employed to have solution A react with solution B in a time of 20 ± 1 s?

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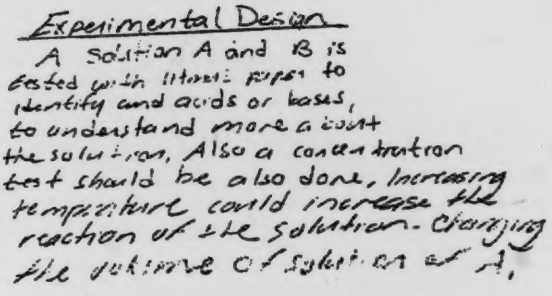
PREDICTION
If 1

EXPERIMENTAL DESIGN
As a control, equal amounts of Solution A and B are reacted with eachother and a time recorded. A manipulation of volume in solution A will be changed to have the reaction between 20 ± 1s.

MATERIALS
- stop watch
- test tubes

PROCEDURE
1. Add 5mL of each solution and record the time.

Figure 4. Priscilla's pre-lab notes.



Experimental Design
A Solution A and B is tested with litmus paper to identify and acids or bases, to understand more about the solution, Also a concentration test should be also done, Increasing temperature could increase the reaction of the solution. Changing the volume of solution of A,

Figure 5. Maureen's pre-lab notes.

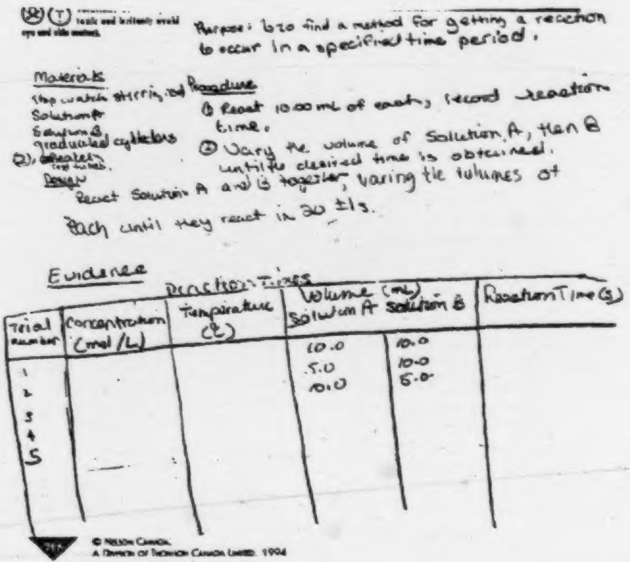
was that they were investigating. Indeed they did not recognize that their interaction had resolved the initial problem posed by the teacher.

A component of what this activity meant to the students dealt with the students' own epistemology of science. Although the students learned from each other, they both did not have confidence in the adequacy of their actions. The consistency of their results which in science would be judged as of high quality in this case was interpreted as spelling trouble. It seemed that they considered the teacher, the one with authority, as the only one who could assure them that their decisions and actions in this setting were acceptable

A third entry strategy is depicted in the actions and interactions of the next female pair, Agasta and Veronica. Although their strategy is somewhat similar to Viet and Manuela's (in the sense that these students seemed to have worked together in the preparation phase) their interactions and level of confidence were strikingly different. Agasta and Veronica seemed confident in the approach they had chosen for their investigation. They appeared to have thought carefully through most of the details and had even constructed results tables before coming to the laboratory. The following is my narrative of Agasta and Veronica's story.

Agasta and Veronica: a Choreography

As these two students walked into the laboratory, there was a sense of purposefulness and readiness. Bags and books put away from the work benches. Lab aprons and safety glasses on, each girl bent down, peeked into the glassware locker and pulled out 100 and 250 mL beakers, 10 mL graduated cylinders and test-tubes. Veronica moved towards the front of the room where she obtained a stopwatch and several white



Purpose: to find a method for getting a reaction to occur in a specified time period.

Materials
stop watch
stirring rod
Solution A
Solution B
graduated cylinders
(2) beakers
test tubes.

Procedure
① React 10.00 mL of each, record reaction time.
② Vary the volume of Solution A, then B until the desired time is obtained.

Design
React Solution A and B together, varying the volumes of each until they react in 30 ±1 s.

Evidence

Reaction Times

Trial number	Concentration (mol/L)	Tempirature (°C)	Volume (mL) Solution A	Volume (mL) Solution B	Reaction Time (s)
1			10.0	10.0	
2			5.0	10.0	
3			10.0	5.0	
4					
5					

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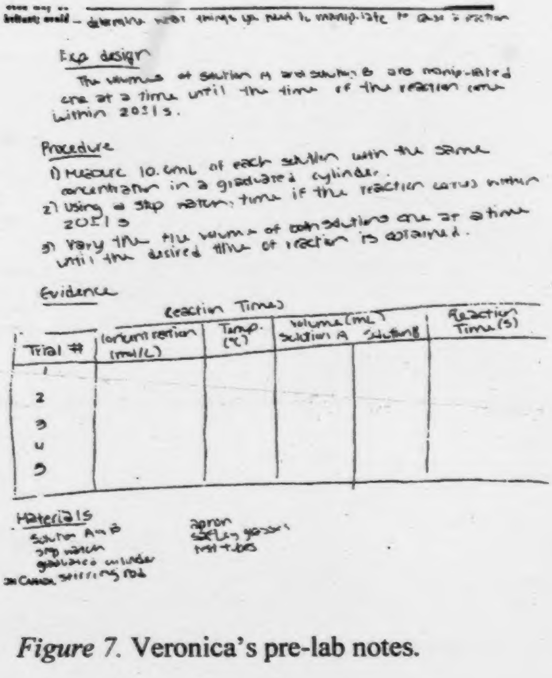
Figure 6. Agasta's pre-lab notes.



— determine what things you need to manipulate to cause a reaction

Exp design
The volumes of solution A and solution B are manipulated one at a time until the time of the reaction comes within 20±1 s.

Procedure
1) Measure 10.0 mL of each solution with the same concentration in a graduated cylinder.
2) Using a stop watch, time if the reaction comes within 20±1 s
3) Vary the the volume of both solutions one at a time until the desired time of reaction is obtained.

Evidence

Reaction Times

Trial #	Concentration (mol/L)	Temp. (°C)	Volume (mL) Solution A	Volume (mL) Solution B	Reaction Time (s)
1					
2					
3					
4					
5					

Materials
Solution A and B
stop watch
graduated cylinder
stirring rod
apron
safety glasses
test tubes

Figure 7. Veronica's pre-lab notes.

paper towels. At the same time Agasta moved to the back of the room picked a wash bottle and filled it with deionised water. They both made their way back to the lab bench. On their bench top were two handouts with students' initial problem solving design hand written (Figures 6 and 7). The students had thought about the result tables; this was different I thought to myself. In all three classes few students came to the laboratory with that level of detailed preparation.

Agasta and Veronica's actions even at the initial stages of their investigation seemed well organized and synchronized. They each seemed to know what the other was doing, moment by moment. From time to time they would stop, check their result tables, talk quietly about them and then move on to the next step. The entire undertaking seemed like a well choreographed dance as they both shared in the work.

"Agasta how does this work?" asked Veronica playing around with the stop watch as Agasta rinsed the two beakers with deionised water and allowing them to drip upside down on the paper towel. With Agasta looking over the shoulder, they both tried to figure out how they would use the watch. Being somewhat familiar with watches they pressed one button, watched, pressed the other button, watched, and pressed the other one again. "Oh, I got it to work, I will put it at zero, the left button resets it to zero and the right starts and stops the watch," continued Veronica. Through trial and error and the immediate feedback presented by the workings of the stopwatch they figured out how they would use it

Once they had the watch figured out, the students obtained the two solutions needed for the lab stock bottles. Back at their bench each girl measuring out 5 mL of the solution they obtained as they prepared for the first trial. With Veronica taking charge of the watch, Agasta poured the two solutions into a 15 mL test tube with no further mixing. After a few moments waiting Agasta, recognising a thin streak of blue starting to form, cried out to the researcher who was standing near by and asked, "When do we know when to stop timing?"

The researcher not wanting to answer Agasta's question responded with a question to help the girls think through the problem they were experiencing. "What do you think? You have to decide."

Both Veronica and Agasta had just watched their mixture slowly turn blue. "I think when it starts getting blue" Veronica replied. The change they had just witnessed started with a show of a few streaks, then more streaks and more and then it was all dark blue. Perhaps these students figured that the start was more distinct therefore they could tell more easily when to start.

In this particular school chemistry class the students had learned how important it was to be consistent in their observation and measurements. Agasta raised that concern. "Well, we have to find a way that will work consistently." She then looked around as if to seek out the classroom teacher for help. But not finding him she turned back to the researcher and asked again, "When do we know when to stop timing?" Her action is not surprising. It was quite legitimate given that students learn early in their school careers that teachers have answers.

Recognizing the problems a small test tube might create the researcher's reply again did not answer the question directly but re-directed the students. She suggested the students try using a different reaction vessel. "What do you think would happen if you used a flask or a beaker? Would it change the appearance of the colour change?"

Realizing that they have to find a way out for themselves, the two decide to follow the researcher's prompting. "Let's try using the beaker. We can put it on a paper towel so we can recognise the change immediately." With that shift in attention different but related knowings emerged for Agasta as she also realized that a white background would help them notice the colour change more quickly.

It seemed that these students had adequately prepared for almost everything, even when faced with an obstacle like knowing how to use the stop watch, they could overcome the obstacle. Again when faced with a second obstacle (when to start and stop timing) they used the teacher or the researcher's help to figure things out.

Occasioned by the researcher's prompt the girls decided to use a beaker instead of a test tube. The test tube was too small to allow them to try different strategies. The students measured out solutions for their second trial and adjusted their procedure accordingly using the 100 ml beaker for their reaction vessel. The appearance of the blue colour was more instantaneous. With another trial run, the colour change appeared again instantly. This was repeatable and thus more reliable, the students concluded. Again the students' experiences were guided by systematic trial and error. They manipulated the volume of one solution in their procedure.

An enactivist framework prompts us to observe cognition as perceptually guided action which brings forth a world of significance. In other words, what students do is an expression of their knowing but that knowing is mediated by students' perceptions that emanate partly from the culture to which they belong. That is, they use cultural norms, expectations and practices to interpret their experiences and to bring coherence to their living. At once culture constrains actions and interpretations and makes them possible.

Agasta and Veronica's understanding of problem solving in these open-entry investigations was similar to that of scientists. Their actions and interactions were similar to those of practising research chemists. They recognised that they were the main decision makers deciding what strategies to try out and how to investigate. In that decision making, they consulted with each other and with other more experienced practitioners (the teacher and researcher in their case, other chemists in the field in the case of practicing scientists). Based on this, it may be reasonable to suggest that they were aware that their decisions and choices were important in their making meaning. They also recognised that other members of this community of knowers could help open up possibilities for their conduct. Their own understanding of what to do; when to act and how to act was important. In this sense they intuitively knew that they were part of the context of meaning making.

It is apparent that they felt ownership of their creation, rushing to get Mrs. Smith to verify their results they give her explicit instructions for the timing as they measured out the solutions. After mixing, Agasta stepped aside, waited a little and then bent over towards the bench top to watch as if to talk to the reaction (seemingly anxious as the colour change apparently took longer than she expected.) Her credibility seemed to ride on this run. Although this run did not give them the results they expected, the two students still had confidence that they could get the reaction to work the way they wanted and proceeded to work with the set up until they succeed. The serious and systematic approach with which the two students approached the task reflect that they addressed the problem thoughtfully and systematically. They knew they could figure it out.

Different students solved their problems and made meaning of their interaction in different ways. Cees and Saskia, in the next story, approached the activity differently. Unlike Agasta and Priscilla who were not only well prepared but had similar approaches to the lab, Cees and Saskia did not both come to the lab equally well prepared. Before they could enter into the investigation they to had to find a place to begin, with each other.

Cees and Saskia: Strategizing in Action

The activities of this pair were selected for the dissertation to depict how the students' entry strategy evolved and how they freely moved from one strategy to the other as their investigation proceeded. In the following interaction.

> After the students arrived in the lab they, got their aprons and goggles and the teacher announced that the solutions for the investigation were on the front bench and each group should collect enough of each solution (about 100 mL) to allow everyone to have enough. Cess and Saskia collected among their glassware four 250 mL beakers, two 400 mL beakers, two 10 mL measuring cylinders, a funnel, a stand, and two medicine droppers. Cees seemingly had some understanding of how to approach the problem even though he did not present a written pre-lab. He got two beakers and proceeded to the front bench to collect solutions.
>
> In the meantime, Saskia spent some time talking to a friend and then finally wandered back to her bench. Once there she pick up the activity handout and began to read. A few classmates passed by and asked her something. With a bewildered look she lifted her gaze, shrugged her shoulders and waved at them as if to say, I don't know, and she went back to her reading. After a while another classmate passed by and said something to her in a low voice. She looked up and waving her hands in the air said "we will see some sort of bubbles and when it stops we will know it's done."

At this point in time Cees and Saskia's actions could be said to be neither coordinated nor complementary. Saskia not knowing how to proceed read the handout and Cees forged ahead doing what he understood of the investigation. Cees' return with two solutions triggered a shift of focus for Saskia who then started working with Cees by helping to label the materials. These two solutions, the objects of the investigation helped to bring the two students to a common focus. This point marked the beginning of coordinated work as conversation about the solutions gradually evolved into conversation about procedure and problem entry strategy.

> Once the beakers were labelled, Saskia lifted each, one at a time, examining the level of the solution. With the first beaker she seemed satisfied that the solution was 100 mL as she uttered to herself, "That's a hundred. Okay." Then she lifted the second beaker as if realizing that the level of the solution was above the 100 mL mark, turned to Cees and pointed to the 100 mL mark uttering, "Hundred."
>
> Cees replied, "Yeah, that's hundred".
>
> The researcher who had been watching the exchange, realizing Saskia's concern about the amount of solution and her persistent questioning commented, "That's okay, it does not matter."
>
> Saskia appeared not to understand the comment. She approached the researcher, pointed to the sink and asked, "if we took too much solution do we have to pour some down the sink?"
>
> The researcher replied, "No, wait until you are done."
>
> Cees also realizing the implication of the questioning replied, "No, we have to take out ten millilitres— we are only reacting with ten."
>
> Cees' explanation seemed to help Saskia realise a possible direction for the investigation. She moved back to the centre of the bench and placed the solution on the bench while laughing to herself and waving to the researcher as if to say, now I get it. Relieved, she uttered, "Never mind!"
>
> With that comment, the stage seemed set to start the investigation. Cees, who seemed to be more in control and clear on how to proceed, took the 10 mL measuring cylinder, moved as if to start measuring solution and explained out aloud "Well, the first one we are going to react the solutions with nothing added."

The level of preparedness and the history that each student brought to this activity clearly had an impact on the student's interpretations of the task, the direction their activities took (at least in the initial stages) and the meaning the students made. Initially, Saskia did not know what the activity was about. Her body language and her responses to other students' queries, at the beginning of the class revealed her state of knowing. At first, she asked questions based on what she thought was a potential line of action.

However, as she continued to interact with her partner, her focus changed to address and make meaning of her partner's actions. Saskia's actions and questions also triggered different actions for both the researcher nearby and for Cees. Although the words uttered by both the researcher and Cees did not specifically spell out what Saskia's actions meant for each of them, they both responded in ways that seemed intended to reassure her that all was well. Her knowing gradually changed as she continued to interact and become structurally coupled with her environment (Cees, the teacher, the researcher, and the setting). With ongoing interaction, Cees was able to interpret Saskia's concern regarding the volumes of solutions in the beakers and the plan of action. Through her structural coupling she was able to make meaning of the investigation thus bringing forth a new world of significance for her. It was only once this new world opened up for her that she and her partner were able to move forward with the investigation. In her written reflection she summed up her experience and admitted that:

> At first, I felt confused and disordered because I had totally forgotten that we were doing a lab that day. Then, I felt incompetent because my partner had a plan of action and I did not. Then he explained to me what we were going to do and I was more comfortable with the lab. When we achieved 20.22 seconds on the second try I was excited and confident in my laboratory skills.

The context within which the students worked offered triggers that students did or did not address conceptually and emotionally. The emotions observed were often about the students' felt sense of self. If the perceived challenge seemed insurmountable, it did not simply mean that the students could not take on the task but it also had the potential to trigger negative feelings about oneself and it lowered their self-confidence. Saskia initially felt confused and incompetent, a judgment that perhaps emerged from her perceived lack of self-confidence because she was not prepared enough to understand what they needed to do. The rest of the account portrays how Saskia and Cees continued their open-entry investigation, trying one strategy after another and eventually having more than one possible solution to the problem. The transcript also illustrates how Saskia's and Cees' actions gradually changed from that which clearly originated and belonged to Cees to interactions that were co-owned and co-initiated, at every subsequent step, by both of them.

> Researcher: (sensed that the students were ready for combined action) So, what have you decided to investigate here?
> Cees: We are trying to make the reaction stop at 20 seconds. We are going to slow it down by adding---
> Researcher: Adding water? So basically what you are doing is manipulating the concentration of your second solution?
> Cees and Saskia: Yeah.
> Teacher: (announced to the class) There are stop watches here and each one is marked with a number. Take the one marked with a number that corresponds to your station.
> Saskia: If we have a stop watch here (pointing to her wrist watch) can we use it?
> Researcher: Does it measure to plus or minus point one second?
> Cees: (instructed Saskia) Just go and get one there.
> (After approximately ten minutes the teacher visited Cees and Saskia to check on their progress.)
> Saskia: How do we know that the reaction is complete? It turns blue after about fifteen seconds and then it gets a little bit darker blue?
> Teacher: You are going to have to make that decision in terms of writing your procedure. You have to decide what you are going to do and then be consistent with that.
> Cees: Yes, it has to be permanent
> Teacher: And of course not only you be consistent but see whether or not the experiment can be consistent in terms of the decision you make.
> Cees: If we decide that 21.27 — that's almost to the time suggested?
> Teacher: With ten and ten?
> Cees: Yeah!
> Teacher: Well, (stopped to think)
> Cees: We are using quite a wide beaker.
> Teacher: I am kind of surprised with that — So you did ten and ten?
> Saskia: Yeah we did it again and got 20.22.
> Teacher: Okay.
> Cees: Let's try it with a smaller beaker and see what happens. (Scribbled something on the paper with their results) We will say this is the larger beaker.

The students at this stage had obtained consistent results that solved the problem by reacting equal amounts of solution A and solution B[8] without even manipulating the variable Cees had initially suggested; that is, adding water to change the concentration of one of the solutions. Realizing that they did not need to change concentration, given the volumes they had selected, they chose to explore a different variable. Cees, again suggested a different variable to manipulate, the size of the beaker they used to react the solutions. Their interaction with the teacher suggested to them that this change of strategy was possible and acceptable. From the teacher's comment,

> Well, all we have to do is make sure we get a procedure that somebody else can replicate and get the same results. That's really the purpose of all this — is to be able to replicate it with the beakers we have. So you can also change the size of the beaker or even the shape of the beaker because we have Erlenmeyer flasks. I do not recall anybody else trying that so why not?

The students chose to follow up on Cees' idea and investigated the size of beaker. Saskia initiated the idea of diameter of the beaker as the measure of size they would consider. They chose the diameter (and not necessarily the volume or the height) of the beaker as the manipulated variable.

> Saskia: Do you have a ruler that we can measure the diameter of the beaker with?
> Teacher: I will look for you. (Teacher brought them a ruler and then visited some other groups. About ten minutes later he returned to their bench.) So, you are manipulating what variable?
> Cees and Saskia: Beaker size.
> Saskia: Especially the diameter of the beaker and we are always pouring B into A.
> Teacher: Beaker size? — The diameter of the beaker. So B is already in there and you are using what volumes of each?
> Saskia: Ten millilitres.

---

[8] . The immediate attaining of the targeted 20± 1s from equal amounts of the two solutions is similar to that obtained by Priscilla and Maureen. However, Cees and Saskia chose to extend the investigation and explore a different variable, the size of the beaker, that they thought could affect their results.

Teacher: So, what you started with in this particular case is what you are still working with and you are manipulating the diameter of the beaker. Okay, now I get to use the stop watch.

Saskia: Oh! You get to use the stop watch (she removed the stop watch hanging from her neck and handed it to the teacher).

Teacher: You have to tell me -- if you were writing this in your procedure when would you tell the person to start?

Saskia: You'll start as soon as the solution A touches the other solution B.

Cees: As soon as solution A touches B and you want to try to pour it as evenly as possible. You don't want to just dump it all at once.

Saskia: And you want to stop it when it turns the darkest blue with no more white streaks in it -- at the darkest point. (Cees, poured the solution from the measuring cylinder into the beaker and allowed two drops after most of the solution was poured in. he waited and watched. The teacher timed the reaction.)

Teacher: Streaks, still some streaks, still some streaks. Oh I don't know if there's a streak there or not.

Saskia: We would stop it there right now. Mmm, twenty point four.

Teacher: You've got it (He handed the stop watch back to Saskia. Then he paused as if to reflect on the activity.) Is there anything you could still change about your procedure here that would make it easier for somebody else, based upon what you saw me struggling with there a little bit, what could you do there?

(Both students stopped to think then Cees, put a white sheet of paper under the beaker and without saying a word looked up at the teacher.)

Teacher: You might want to repeat it with the paper underneath. And if that is going to be part of your procedure, you might want to make sure that it works. You can do it at this point to refine your procedure. You've got the results now you are essentially at the point where you want to fine tune your procedure (teacher left the group to visit other groups. Five minutes before end of class teacher checked back on Cees and Saskia again) Trying out a new vessel here?

Saskia: Yes (He mixed solutions in an Erlenmeyer flask with a white sheet of paper underneath the flask.)

Cees: That's seven centimetres in diameter.

Saskia: Twenty-two point one.

Teacher: (Cautioned the pair that there was no time for another trial) Report your best results.

Cees: Best results based on what?

Teacher: Of course your procedure is going to be the same isn't it? So report all of your results for this particular one. Report the best procedure but give the whole range of what happened here because really what you are doing, you are getting kind of a staged result. At this point in time we ran out of time, these are the results we got and there is nothing wrong with that.

Saskia's initial feelings of not knowing how to proceed did not last long as she started interacting with her partner and agreed to adopt the experimental design her partner proposed. The students progressively negotiated their course of action although Cees initially seemed to lead in making decisions or suggesting options in their problem solving strategy. Saskia's interactions gradually became more assertive, her confidence level gradually improved with the extended history of structural coupling and she became more actively involved in the physical manipulation of objects, in offering ideas to be tested and in interpreting their observations. Saskia demonstrates this increased confidence and ownership by suggesting a creative procedural solution to the notion of beaker size. She seemed to know intuitively that the variable had to be measurable for them to be able to ensure consistency. The also chose to keep the transferring of one solution to the other constant by "always pouring B into A" (Saskia). The problem solving approach also gradually shifted from one originated solely by Cees to one co-owned and co-directed by both students. Although these two students arrived for class that day very differently prepared, the open-entry laboratory activity provided a space for them to arrive at a shared solution derived in action.

Students' Problem Entry Strategies

In this open-entry activity meanings and coherences emerged from the interactions that took place. Both the environment and the students transformed each other by offering each other flexible and yet restricted possible pathways of interaction. Students' ways of knowing and their histories allowed them to interact in some ways and not others. The materials and the environment also allowed some interactions and not others. In this sense both environment and students co-determined and co-specified meanings that emerged. A different world of significance was brought forth in this high school chemistry laboratory in which students were recognised and acted as active members of a knowing and therefore a doing community.

The accounts of students' interactions given above when taken together show a variety of entry strategies students used. For instance:

- Manuela and Viet's interactions exhibited extended structural coupling of both students
- Agasta and Veronica's interactions also exhibited extensive structural coupling and seemed choreographed as if they had previously agreed and rehearsed what each would do
- Priscilla and Maureen entered the investigation with different understandings as reflected in their pre-lab notes and seemed less prepared. They eventually used Maureen's approach, they and stumbled on to a solution and
- Cees and Saskia's initial interactions seemed uncoordinated and non complementary. When they started working together, they used Cees' ideas and gradually developed a group strategy in action.

The accounts also indicate the different levels of preparedness students came with to these open-entry investigations with.

Although this was not a major focus, in selecting the student pairs I was aware that research in science education has tended to suggest that gender influenced the kinds of meanings derived in school. I therefore selected different male – female combined pairs to see if there were any observable differences in students' interactions, in their relationships and also in the meanings they made. The interactions between the different gendered pairs seemed different. When a pair was the same (all boys or all girls) each student tended to interact openly contributing to the interaction as co-equals. With mixed pairs, there seemed to be a general tendency for one student to defer to the other. In the interaction between Saskia and Cees, Saskia deferred to Cees' approach although she sought to understand what it was they were doing. In the interaction between Peter and Paula, Paula seemed to wait for Peter to answer the teacher's questions before she came up with her own response.

Students' initial actions were hesitant and tentative as they checked with each other, with the teacher, the researchers and other groups. Although the teacher did not stipulate what they were to do, in many cases his comments and advice were based on the students' results and their ideas. Initially the students tended to ask questions and sought the opinion of either the teacher or the researcher and gradually they made more statements and suggestions of their own ideas to each other as they became more confident and more independent. For instance, when Cees mentioned that they were using "quite a large beaker," that was why their reaction was slow; the teacher picked up that idea and used it as a clue for something they could pursue. Based upon their own thinking, the teacher suggested that the size of the beaker and he added shape, were possible variables that could be significant for them. Students were allowed to investigate these ideas. A copy of part of Saskia's report is given in the section on communicating the activity to illustrate the kinds of scientific meanings that emerged for her, particularly the kinds of variables that became significant in her meaning making.

The different pairs of students had prepared differently for their activity. In each of the two pairs comprising Manuela and Viet and Veronica and Agasta, the students had worked together and had prepared quite extensively which enabled them to immediately engage the activity and to shift focus more readily and recognise different possibilities when different triggers emerged in the interactions. The other pairs with Cees and Saskia and Priscilla and Maureen seemed to have worked independently preparing for the activity. Their interactions seemed to be somewhat limited, at least in the initial stages as they tried to figure out where each one was coming from. Saskia who had forgotten about the activity started off rather shaky asking most questions and gradually becoming more confident as they worked their way through. Cees on the other hand started off more prepared and more in control, directing the initial stages of the activity and gradually becoming less and less directing as Saskia became more aware of what they were doing and started acting in ways that were complementary to Cees' in finding a solution to their problem. Although Cees and Saskia obtained a reasonable result with their first trial like Maureen and Priscilla, they chose to extend the investigation and make it more interesting for themselves as they explored the effect of both the size and shape of the reaction vessel in the reaction.

The participation of the teacher, the researcher, each of the students in this and other groups was essential in the evolution of the different problem entry strategies that emerged for this activity. Everyone played a role within this community of knowers. Each one's history of interactions with phenomena and how they each prepared for the activity came to bear in their entry strategy. Participants acted as triggers for one another as they brought forth, together, worlds of significance in their interactions. Different variables emerged as significant for different groups.

Students Negotiating Meaningful Results

Observations and measurements of phenomena, by themselves, often do not have any meaning. They have to be interpreted by an observer within a community or culture and communicated as evidence. In these investigations participants had to agree on what they would accept as useful results and negotiate what meanings or evidential information they would bestow on them. Students had to agree on the results at each step. In addition they had to negotiate and agree on the meanings they bestowed on these results. In the following section, students negotiated the results they obtained and the meanings these results had for them as they continued with their investigations. The results and the meanings of these results that emerged for the students were used to determine subsequent viable action. Accounts of two groups comprising Manuela – Viet and Peter – Paula, are presented.

Manuela and Viet

> Teacher: So, how are the temperature guys?
> Manuela: We tended to discover that when we lower the temperature of B and leave the temperature of A plus (not lowered) then the time drops.

The students had established a trend in their results that guided their actions at the time. With subsequent trials the apparent trends seemed to change and this created a moment of uncertainty for the students that forced them to revisit their interpretation of the results, the meanings that emerged for them and the procedure they used to get these results.

> Teacher: So you are back to — Okay. (Solution changed colour to a light blue and Viet stopped the watch immediately.)
> Manuela: No! It has gone up again!
> Viet: Yeah. That means B can't be kept too low.
> Manuela: Yeah (paused).
> Viet: So keep both at fifteen degrees.

Manuela: Fifteen.
Viet: Let's keep both at fifteen degrees and see what happens.
Teacher: So you are switching your strategy again here, are you?
Viet: Yeah. Extreme temperature — it doesn't work.
Teacher: So, What is guiding you here, in terms of making your decision?
Viet: Time. (Pointed to the record sheet with the pen he was holding)
Manuela: Time. Every time we lower the time (indicating on the record sheet) temperature drops. So, oh! No. Wait! That should be the other way around.
Teacher: Oh, here we have a drop in temperature but the time was less. What do you think about that? Would you expect that?
Manuela: No.
Viet: No. We can't be too low.
Teacher: You can't be too low?
Viet: The temperature can't be too low.
Teacher: Oh. Okay, so you are thinking that the manipulations are some how messing things up when the temperature gets too low? Is that what seems to be the results here?
Viet: Yeah.
Teacher: So that's why you are going back now to 15 and 15 is it?
Viet: Yeah.

At this point the students did not seem to think that there could be other variables interfering in their investigations. They therefore concluded that the change in their observed trend was because at lower temperatures the reaction behaved differently. They therefore needed to work at temperatures higher than five degrees despite the fact that this seemed to work against what they think should be happening. The teacher, realising that the students could perhaps find this to be a possible road block for them, offered a prompt which if considered carefully suggested other possible ways of acting.

Teacher: The last time (pointed at their record sheet) you did 10 and 10 and you got 15, then 5 and 5 you got 16. So you are thinking 15 and 15 will move you towards ---
Manuela: I am not sure.
Viet: (Stretched his words hesitantly in a lower voice) It should.
Teacher: Ok. I will check back with you later to see how that is going. (Gwent to leave and then stopped. There was a brief silent pause.) I think there's something that is messing up your work as well. (Then he left the group and visited other groups. Later the teacher revisited the group.)
Teacher: How come you are not putting ice right into test tube?

Viet: If the ice melts ---
Manuela: We will be diluting the solution.
Teacher: Ok. Why don't you want it diluting?
Manuela: Because we are manipulating temperature only. Okay.
Viet: That would give us errors.
Teacher: So you don't want to manipulate more than one variable.
Manuela: Yeah.
Teacher: Wouldn't it be more fun it you did?
Manuela: Yeah that's what I thought.

At this point the students ran out of the solutions they had collected initially and they went to collect more from the stock bottles. When they tried the reaction at some of the temperatures they had already tried and at even lower temperatures their time was still far less than what they had obtained originally suggesting that there might have been something different with the solutions. The students checked with the student teacher Mrs. Smith[9] and Dr. Meulenberg about what to do. They decided to stop and write up what they had done so far and explain why they could not continue or re-do the entire activity over again.

Regarding the learning of chemistry and the doing of chemistry, several possible conceptual ideas are suggested in last ten lines of the excerpt. The idea of contamination of the reaction mixture, the idea of changing concentration of solutions which emerges out of the interaction and the idea of controlling one variable at a time to obtain reliable and conclusive evidence. Although not all these ideas publicly emerged from the setting, the teacher's question, "How come you are not putting ice right into the test tube?" offered Manuela and Viet a chance to think, evaluate and be able to justify to themselves the viability of their procedural enactions.

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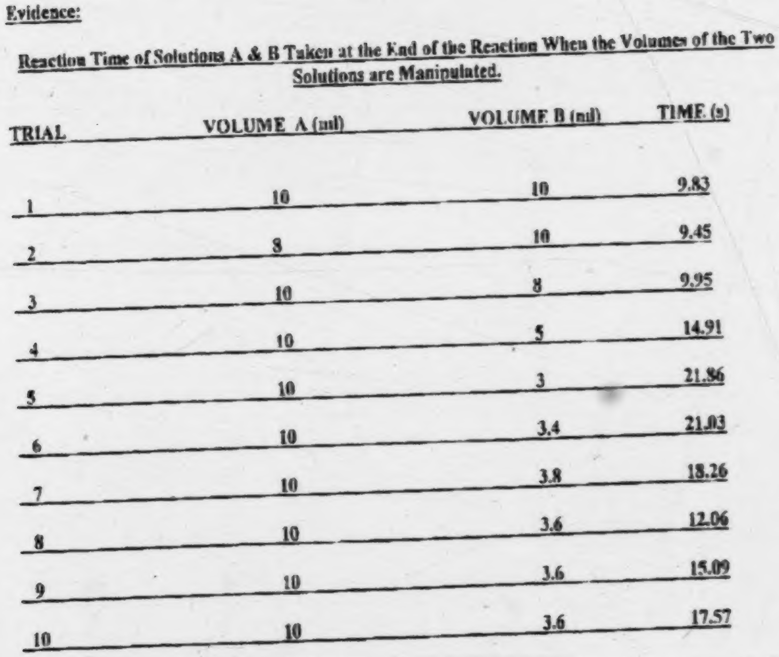
[9] Mrs. Smith was the student teacher in this class and taught some of the lessons prior to the investigations. So she participated in this research as a co-teacher.

The next excerpt describes the investigation by a male-female group, Peter and Paula, from one of the Chemistry 30 IB classes. Several scenarios had been brought up in the pre-lab discussions regarding possible variables and how they could be manipulated or controlled. For almost all the groups, the initial trial was only informed by the general everyday laboratory practise of the classroom. Although there was more choice than in most laboratory work in terms of what apparatus and what reagents to use, the choice was not endless. The available choice, in a sense, presented some constraints to the possibilities of what students could do which, in turn, guided them. The second trial and all the subsequent trials were informed by the results of the previous attempts. This required students to stop, evaluate the trends arising with the results and then deciding what the next move would be, to bring them closer towards achieving their goal.

Peter and Paula's Number Game

Up to this point, Peter and Paula had carried out several trials, repeating each trial to ensure consistency of their results (they did not, however, record in their formal report a record of their repeat trials as seen in Paula's results (Figure 8 below) and a recognizable trend had started to emerge for them.

The students had just completed another trial informed by the trend and were struggling to make sense of their results as the teacher approached them. The results of trial 8, 9, and 10 were a repeat of the same procedural step but they presented a challenge for the students because they all gave a different reaction time from what was expected given the trend that was emerging from their previous trials.



Evidence:

Reaction Time of Solutions A & B Taken at the End of the Reaction When the Volumes of the Two Solutions are Manipulated.

TRIAL	VOLUME A (ml)	VOLUME B (ml)	TIME (s)
1	10	10	9.83
2	8	10	9.45
3	10	8	9.95
4	10	5	14.91
5	10	3	21.86
6	10	3.4	21.03
7	10	3.8	18.26
8	10	3.6	12.06
9	10	3.6	15.09
10	10	3.6	17.57

Figure 8. Results from Paula's laboratory report.

Teacher: What is happening here folks?
Peter: (looked down and seemingly unsettled) I don't know. I think everyone messed up or something. We have actually —.
Teacher: (examined their results) So, you were getting really close and all of a sudden you are —
Paula: We are getting like very different results for three point six.
Teacher: So you were at 3.4, 3.8, getting very close to your result, chose the middle 3.6 and all of a sudden it's jumping all over the place. Any ideas why mother-nature might be doing this to you?
Paula: (clutched the stop clock and trying to think of a possible source of this discrepancy) Maybe we are not stopping the clock right or something because it is hard to tell when —
Teacher: So, what procedure could you use so it is easier to tell when to stop? How might you modify your procedure?
Peter: (exchanged glances with Paula and looked up towards the teacher with a smile) Maybe you could, like, before the reaction actually finishes, just when it, like, starts that's when you stop the time instead of waiting for it to finish.
Teacher: Okay, because the edge of something is easier to determine than the middle of it or towards the end.
Peter: Yes, because it has turned so dark already.

Teacher: Okay, we will see.

(After several minutes the teacher came back to see what Peter and Paula were doing.)

Teacher: Where are you guys at now? What has been transpiring since I was around here last time?

Peter: We started ours again. We are now, like, doing it at the beginning since, like, when the reactions starts instead of, like, when it is finished. So we have changed our experimental design again

(The results that these students obtained were seen by the students as arising not only because of manipulating the stop clock as Paula initially suggested but perhaps because of their entire timing strategy. They therefore repeated their investigation using a different timing strategy.)

Teacher: And how is that working for you? Is that working better?

Paula: No. Now our results are more confused.

Peter: But I guess it would work better later because it is more accurate since it is now easier to judge when it is done. Now since it is easy to tell when it starts, it is very easy to tell, you can react faster and know when to stop the stop watch.

Teacher: So the actual precise point is easier to judge, but then the question is

Paula: the results —

Teacher: Are the results variable or not? So the results are still variable. (Paula commented, "Yeah.") What would be best? You tried the beginning, you tried the end. The middle is a problem, too, isn't it? (Peter: "Yeah.") So, what else could you do to try to get the results to be precise as (turned towards Peter) you are providing the criteria or consistent as your (turned to Paula) criteria? Is there a procedure that you could use that would meld those two criteria together to give you the kind of thing that you want?

Paula: We will start it all over again.

Peter: I guess if we take averages of the ones that you did for the final and take the ones that you did for the initial, you could add the results together and combine them and find the one that is in the middle.

Teacher: So that would be like a statistical solution to your problem. What would be a lab procedural rather than a calculation procedural solution to your problem? Anything you can think of?

Peter: Well, I can't think of any thing.

Teacher: Could you get all of it to turn blue at once?

Paula: No, I don't think so.

In this excerpt the results are still not easy to interpret. The students' interpretations also differ as Paula suggests a problem with consistency and Peter's concern is accuracy. The students offer different possible solutions to address this challenge. Peter offers a statistical solution. This triggered questions from the teacher that enabled them to shift their focus to possible procedural solutions.

> Teacher: Anything that you might be able to do in the procedure to make the beginning and the end to be the same point?
>
> Paula: Mix it? (Shook her hand to indicate the mixing) to mix it while we are pouring?
>
> Teacher: If you mixed it then you wouldn't have a beginning or an end. You just have a merged endpoint wouldn't you? (Both students nodded.) Do you want to give that a try? Anyway you just have one or two minutes here. Peter and Paula made one more trial and stopped.

From the stories of both groups, the negotiation of meaning of results was not just a negotiation of numbers. It was also a negotiation of possible interpretations and possible procedures. In these conversations, all participants had to be tuned in to listen carefully as the different interpretations offered different ways of acting or doing. The teacher was an important co-participant in these negotiations as he listen to the students' emergent knowing and from time to time offered students a different interpretation or prompt that invited them to look differently.

Communicating the Activity

To conclude this activity, a class post-lab discussion was conducted on the next session. The teacher led the discussion by asking questions and students shared some of their experiences. The groups discussed their challenges, what they could have done differently and the lessons they learned from the experience. Students were requested to write a reflective note to be handed to the researcher and a laboratory report that both the teacher and the researcher could use for their different purposes. The students' laboratory reports communicated their problem solving strategy. In the reports students presented their different problem statements, and investigative designs. They indicated the different variables they addressed showing which ones were controlled, which ones were manipulated and which ones were responding. They also analysed and evaluated their investigations. Mostly the reports followed the tradition of school chemistry lab reporting of which students were familiar. The significant difference in their reporting was that they reported their own problem, their own design, materials, procedure, results and analysis. In their reports, Peter and Paula, for instance, chose to report their closest results and therefore changed the problem statement for the activity from 20 ± 1 s to 18 ± 1 s as shown below.

Problem: What technological process can be employed to have solution A react with solution B in a time of 18 ± 1 s?

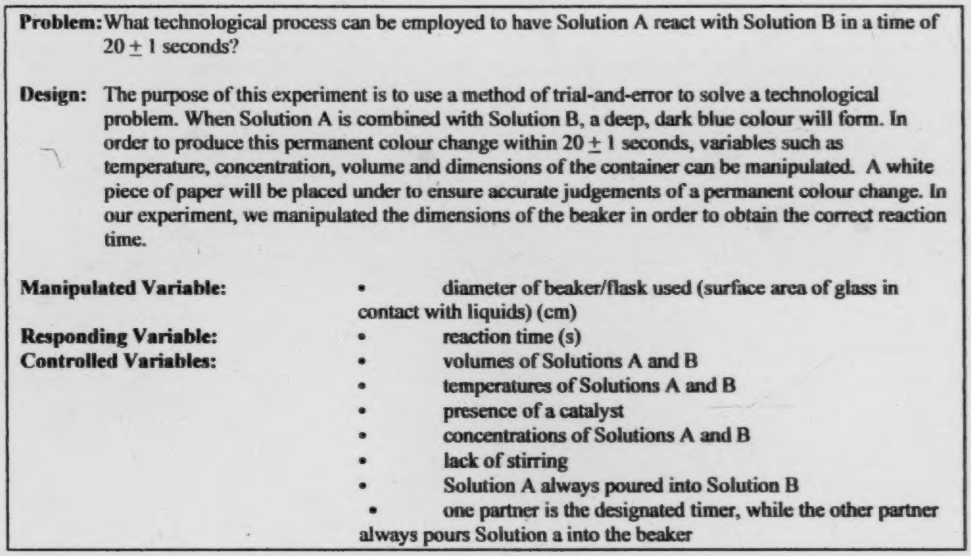
Analysis: According to the evidence, our experiment design was a success as this experiment gave us a time of 18 s ± 1 s. The manner we came about this was:

(1) We first obtained all materials needed and put on all safety gear.
(2) We obtained and carefully measured out the amount or volume of the solution in a graduated cylinder
(3) Next we put …
(7) By trial and error process we narrowed down our method to about 3.5 mL of solution B with 10 mL of solution A

Since we did get around 18 ± 1 s our results are verified. Although it was a success, I found several flaws in this experiment such that it was difficult for us to judge whether the reaction was complete or not throwing off the time. Also since we used the same beaker for all the experiments, cleaning was essential which may lead to contamination. Instead I believe a way to improve our experiment design to increase accuracy at the time would be to swirl the solutions around in the beaker so that both solutions are constantly mixing.

Figure 9. Part of Peter's lab report.

Students' reports differed and reflected their different problem solving strategies. Their style of reporting also differed although many adhered to the format suggested in the laboratory hand out provided during the preparatory phase of the investigation. A portion of Saskia's report is presented below (figure 10) to show the different reporting styles students used.



Problem: What technological process can be employed to have Solution A react with Solution B in a time of 20 ± 1 seconds?

Design: The purpose of this experiment is to use a method of trial-and-error to solve a technological problem. When Solution A is combined with Solution B, a deep, dark blue colour will form. In order to produce this permanent colour change within 20 ± 1 seconds, variables such as temperature, concentration, volume and dimensions of the container can be manipulated. A white piece of paper will be placed under to ensure accurate judgements of a permanent colour change. In our experiment, we manipulated the dimensions of the beaker in order to obtain the correct reaction time.

Manipulated Variable:
- diameter of beaker/flask used (surface area of glass in contact with liquids) (cm)

Responding Variable:
- reaction time (s)

Controlled Variables:
- volumes of Solutions A and B
- temperatures of Solutions A and B
- presence of a catalyst
- concentrations of Solutions A and B
- lack of stirring
- Solution A always poured into Solution B
- one partner is the designated timer, while the other partner always pours Solution a into the beaker

Figure 10. Part of Saskia's report.

A copy of Paula's laboratory report is given in Appendix C.

Living the Experiences of the Iodine Clock Activity

At the end of the lab sessions, while students were cleaning up, the teacher and the researcher interviewed the students about their experiences. These informal interviews gave a picture of how some students' immediate reflections about the activities. Frequently, the interviews captured students' immediate emotional state which tended to indicate the level of connectedness to the investigative process students felt. In communicating about the investigations, I was interested also in students' lived experiences of these activities, experiences that are often never talked about in a high school chemistry setting. These experiences enabled us to listen to students' felt frustrations and joys. In the following interview, Liz and Meg had just completed the iodine clock reaction and were busy cleaning up their glassware. The teacher approached the students and started to chat with them.

> Teacher: What did you think of the lab?
> Liz: I'll never do it again!
> Meg: I don't like making my own procedure.
> Teacher: You don't like making your own procedure, how come?
> Meg: There are so many things that can go wrong.
> Liz: Not enough time.
> Teacher: Not enough time, yeah Okay.
> Meg: Yes. We needed longer time for the lab.
> Teacher: Okay. Would you like the lab better if you had enough time?
> Liz: Yeah!
> Meg: Yes. If we had lots of time it would have been fine.
> Liz: Because we are always rushed.
> Teacher: If you had more time would you like to have more labs like this?
> Liz: Yeah.
> Meg: Yes (nodded several times).
> Teacher: So it is not that you don't like labs where you don't have procedure.
> Liz: The titration ones are fun!
> Meg: No (laughed). It is just that I get frustrated.
> Teacher: So you had two variables changing there - the time variable and the no procedure variable.
> Meg: Yes. It is just that sometimes when it doesn't work with in a certain time. You start getting frustrated.
> Teacher: Okay. And you don't like being frustrated.
> Meg: I don't do well when I am frustrated. No.

Students' experiences of the activity varied. Given that each student brought his or her own history and expectations to the activity, their experiences also varied. A sample of the students' reflections on their experiences of the iodine clock reaction is given of below. Students' reflections expressed different kinds of meanings. Some of these dealt with scientific ways of doing chemistry, some with scientific concepts. Other meanings dealt with what they learned about the nature of the activity while others dealt with how they saw themselves as a result of doing the investigation. A discussion of these is presented in the section on; what meanings – the iodine clock activity? Although not primary to this dissertation, a comment about the teaching experiences is offered here perhaps to point to some of the lessons that I learned from the iodine clock activity that may have implications for teaching open-entry activities.

> Student 1: According to me, the lab was indeed challenging but enjoyable at the same time. The trial-and-error approach to this experiment was also different to the usual labs that we have done this year; so in this sense, it was "refreshing." I also appreciated the opportunity for us to evaluate our procedure (the volumes of solution A and B in my case) and make the appropriate changes on the spot, not to mention under time pressure. From what has been said, the experiment was most successful.
>
> Student 2: From a scientific perspective this investigation was very beneficial. It was crucial in understanding the basic concepts of the theory of rates of reactions. The skills used gave a background for future scientific processes where time is a variable. This investigation helps one greater understand the immense number of variables which must be kept controlled in order to maintain a reliable conclusion. This investigation is acceptable viewing it from a scientific perspective.
>
> Student 3: I felt that the lab was fun and that it developed critical thinking skills on how to solve a problem. However, I felt that the equipment used was not precise enough to yield reliable results. The quantities or reactants were too small and thus allowed for great uncertainty. Larger amounts should have been used. I felt that the easiest variable to control was the concentration of the reactants.
>
> Student 4: I found that the lab was pretty frustrating at times. We would often have a volume that would give us a time close to 20+ 1 s, but not close enough. Then we kept having to change our volumes to try and keep getting closer to the needed time. Also, we tried to repeat the test when we thought we had the correct volumes but we didn't get very consistent results.
>
> But it was interesting to see the effect that a change in volume of each solution had on the time of the reaction - it was often not what we expected. Often we thought a particular change would speed up the reaction, but it really slowed it down.
>
> Student 5: I thought that this lab was much more difficult than our ordinary labs, because of the lack of procedure. Without a detailed step by step

procedure, there is more room for error. However, this lab was also very interesting. There was much more freedom, in terms of what we could do. Overall, I liked the lab and enjoyed making our own procedure for our unique lab.

Student 6: Attempting to obtain a specific result in an experiment (in this case, a 20 second reaction time) can sometimes be relatively easy, since you know what your answer should be. However, it can prove to be a challenging task, as there are many ways to go about doing your experiment, and every manipulation in your design can potentially lead you towards your goal - or lead you astray.

In our experiment, my partner and I did end up changing our manipulated variable, because of difficulties in conducting an appropriate experiment. After conducting several trials, it is sometimes frustrating that we were not reaching our desired results, especially with certainty, as our allotted time was running out. In the end, though we managed to obtain a consistent result, which we could use in answering the problem in our investigation.

Student 7: This experiment was a good learning experience. By not having a defined procedure, we were able to exercise our analytical skills that we would not be able to use normally. In my opinion, these labs are good to do from time to time.

Student 8: The lab made me feel independent on the whole. I was able to decide on my own which variables to control and which to manipulate. I didn't have to follow step by step a procedure from a book, and basically "I was on my own." In the end when I was able to get results for the variable I decided to manipulate, I felt triumphant and proud of myself.

How was the teaching of the iodine clock activity experienced? The teacher and I spent a lot of time as we went from group to group checking progress, and explaining to students:

- Their role in making decisions about their procedures, and overall investigation strategies
- The importance of careful observation and recording everything they did
- The necessity of maintaining consistency in their actions and procedures

For some students a bit of time was spent figuring out how to use the stop clock provided. From time to time students were caught up in a situation where there were one or more confounding variables that they seemed not to be aware that that needed to be addressed to help make the results more reliable. Through questioning and working through a trial or two with students we were often able to draw students' attention to this possibility which led them to find ways to resolve it if they deemed it necessary e.g. contamination in Manuela and Viet's engagement or Peter and Paula's end-point determination. Overall both the teacher and I learned from the interactions as well. A significant part which in a way was similar to students' learning was dealing with uncertainty. We also were at times hesitant about deciding how much help to give students and what form the help should in. We struggled with this because giving too much help could deny the students the chance to actively engage and personally develop their own meaning from the investigations. In these open-entry activities we had to recognize that challenges presented personally meaningful learning possibilities and therefore we needed to carefully find a balance between helping or removing obstacles and allowing opportunities for learning a process that required careful listening and a readiness to accept and deal with your own uncertainty.

Co-determined for Co-existence: A Braiding of Minds, Hands, and Lives

The stories of the students in each group reflect a level of complexity which could be interpreted using several of the ideas of enactivism. Students are structurally coupled at several levels, for instance at one level there is student-student (Manuela-Viet, Priscilla-Maureen, Agasta-Veronica, Peter-Paula) coupling, where not only ideas of one student trigger the behaviour of the other, even the action of one complements that of the other. The entire preparation for the activity with little exchange of words as to what to do in Agasta and Veronica's case, for instance, culminating in the figuring out of the use of the stop watch, displays a sophisticated process of meaning making where one's action has meaning for the other and prompts the other's action towards getting the objective achieved. With Agasta and Veronica, both students seemed to be more in control. They were both well prepared and seemed to have worked together in preparing for the activity as they equally pulled their weight in achieving the solution. Their confidence level matched their level of preparedness.

Priscilla and Maureen had worked independently in preparing for the activity and came with different understandings and interpretations of what to do to start the activity. Although they were both not too sure what to do, their discussion about the plan of action at the start of the activity, coupled with observing what other students in the class were doing, resulted in Priscilla changing her mind about her strategy and adopting Maureen's. Both students' confidence in their interpretation of their results was shaky as they related to the teacher what they did and what they thought was happening. The relief expressed by both students when the teacher confirmed their results and actually informed them that they had found the solution to the problem reflected their initial lack of confidence in what they were doing.

At another level, there is student-researcher coupling where the speech and action of one prompts behaviour in the other. The discussion about the timing of the reaction and the recognition of endpoint between the student and the researcher in the presence of the teacher exemplifies another level of coupling. At yet another level the student-teacher-student coupling exhibited by Peter-teacher-Paula in the negotiation of what a meaningful result was or the Manuela-teacher-Viet coupling in their determination of how to reduce contamination and to increase efficiency of the process was especially significant given the amount of effort and the length of time the students invested in trying the different options. At another level there is also coupling of all participants with the setting. In this given laboratory setting with a limited time schedule the dynamics of student and teacher interaction may trigger a certain level of purposefulness and create a level of urgency for finding solutions to the problem. Many students commented that they felt rushed or did not have enough time and that was their main source of frustration with this type of activity.

Scientific Meanings

Some groups decided to solve this technological problem by manipulating the reaction temperature, others manipulated volume, concentration (by changing the volume of water added), beaker size, type of water used to change concentration, ratios of solutions, and/or swirling or stirring. The majority of the students manipulated the volume of one of the solutions while three groups manipulated temperature. Temperature seemed to be the most challenging and most difficult to control. All the groups who attempted this approach struggled, first and foremost, with how to ensure and to maintain the temperature at a level they desired. Their intuitive first step was to try to slow down the reaction by reducing the temperature using an ice-bath. The challenge that seemed to occupy most groups was; do they cool one solution or both solutions and then mix at room temperature, or cool one solution or both solutions and then mix at a lower temperature, or cool the reaction mixture only or all solutions. Different groups did a combination of these. With so many possibilities for the given time period, it was easy to over look some detail. For instance, in Manuela and Viet's case, the students did not dry the outside of the measuring cylinders after removing it from the ice bath before pouring it in to the reaction vessel as a result they were not able to develop a consistent and reliable procedure despite their hard work. The discussions revealed a lot of frustration from these groups; however, these students also seemed to have learned a lot from this experience about the nature of science investigations. Comments made by the students during the class discussions after the activities reflect this diversity of meanings and feelings.

What Is an Observation?

Human observation like most bodily action is pre-verbal and not pre-meditated. It involves changes of body states that remain lodged, memorialized as traces in the memory of neuronal networking even when the experience has been formalized verbally. Learning chemistry like learning the other sciences involves learning how to make meaningful and relevant observations. It also involves being able discern what the observation implies within the bigger picture of the theory and the discipline being studied. The meaningfulness and relevance of observation in chemistry is negotiated within the culture of chemistry. Learning high school chemistry meaningfully involves being able to sharpen your senses in particular ways. I remember starting my graduate studies in chemistry and having to learn to adjust my notions of what small amount meant. I had to learn to appreciate that obtaining 3 mg or 4 mg of material in an investigation was very significant and that you could still do important tests with that amount. I had to re-learn to focus my attention to be able to see things I could not see before. Students learning high school chemistry too have to re-learn how to make observations and know what is significant in their investigation to be able to make sense for themselves.

The iodine clock activity allowed students to learn to observe carefully end-point changes as well as trends in results that they could use evidence. Some students' observations which emerged incidentally later developed significance that required students' investigation. Saskia and Cees' beaker size and shape, Terrilyn's tap water use and Glen's sequence of addition of solutions are a few of the examples.

Emergence of What Constituted a Variable

Students' initial actions were hesitant and tentative as they checked with each other, with the teacher, the researchers and other groups. Students progressively negotiated their course of action. The participation of others (within the community of knowers) in the emergence of the significance of the variables is essential in the evolution of the activity.

What emerged as significant for the students as they engaged in the open-entry activity? For different students different things became significant enough to their activity. The significance of these variables emerged from the actual doing of the investigation sometimes emerging as a problem encountered during one trial or as an alternative path of action and became the focus of investigation. At each step of their investigation, students had to stop, think, evaluate their results, their procedure, and their skills and decide the next course of action based on what they thought made sense given what they had achieved or not achieved. Discussions within groups, between groups, with the teacher, with the researcher, and at times with other resource people present in class led to different decisions and plans of action. Some students decided that the diameter of the reaction vessel was a significant variable to investigate while others examined the effect of using tap water as compared to deionised water for dilution of the solutions in the investigation. Others investigated the order of addition of solutions. Timing was a common problem since it was dependent on end-point determination. Students did not know how to manipulate the procedure to ensure a consistent repeatable end-point determination. By trial and error and working with a more experienced adult the students were able to come up with strategies to solve the problem. Students learned to control for as many variables as they could to make their reaction work the way they wanted it to.

Pedagogic Meanings

What did students learn about the investigations? Several students found the investigations interesting, challenging, refreshing and enjoyable. Some mentioned that "it developed critical thinking skills" while others also found it frustrating at times. The students' frustrations often arose from students' felt time pressure.

Several students observed that the lack of procedure in the iodine clock activity and the ability to evaluate their own procedure allowed them to be creative and develop ownership of their creation. However, students expressed concern about the possibility of introducing errors and perhaps uncertainty in their investigations.

Students' reflections suggest that as a pedagogic tool, the iodine clock activity offered them a different way of learning chemistry which most of them seemed to find enjoyable. It allowed them make their own contributions to the investigation and to develop personal meanings that they could identify with and defend at times.

Self-Referential Meanings

Some of the meanings that emerged for students were self-referential. They taught students about themselves. Some of these meanings were negative due to students' perceived self-confidence as they encountered uncertainty. Many of these meanings were temporary and as students started experiencing some success with their investigations their self-image also changed. "The lab made me feel independent on the whole". (Student 8) These experiences may inform our teaching and help us listen more closely to students. They suggest that students' apparent lack of competency need not be treated as a learning deficiency but rather as a prompt for teachers and others in the setting to listen and to interact with the student.

CHAPTER SEVEN

CONSTRUCTING A POP CAN CELL

The second open-entry activity was taught as part of the Chemistry 30 electrochemistry unit. In this unit the class had already covered some related theory on oxidation and reduction reactions and on the simple cell. As part of the unit the students had done experiments in the laboratory with voltaic cells using salt bridges and porous pots. This open-entry activity was a typical technological problem-solving activity that involved designing, testing, and evaluating a product; in this case, a pop-can cell (see Figure 11). The activity did not necessarily require students to know or use any abstract theoretical concepts[10] because of its empirical nature. Students were provided with a wide range of materials from the start, and the environment was flexible enough that they could ask for any additional materials. Students were given a task to design the best electrical cell using aluminium pop cans, copper, and/or carbon electrodes, and solutions of sodium hydroxide, hydrochloric acid, and sodium chloride. The pop can was the other electrode. Other equipment available to students included multimeters, ammeters, and voltmeters. Students were provided with a handout outlining the activity, with a diagram drawn on it showing the basic set-up (see Appendix A). In presenting this in this chapter, I focussed on students' constructions, paying attention to how they assembled their cells and how they used measuring instruments and other equipment. Unlike in the previous chapter, my accounts of students' interactions do not focus on their various entry strategies, but rather on their manipulations. I have used transcripts of four groups of students.

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[10] *Theoretical* is used in this context in the way the teacher used it in class with his students. His usage made a distinction between empirical and nonempirical (theoretical) concepts. Therefore students' perspectives may not be theoretical because they can be developed empirically.

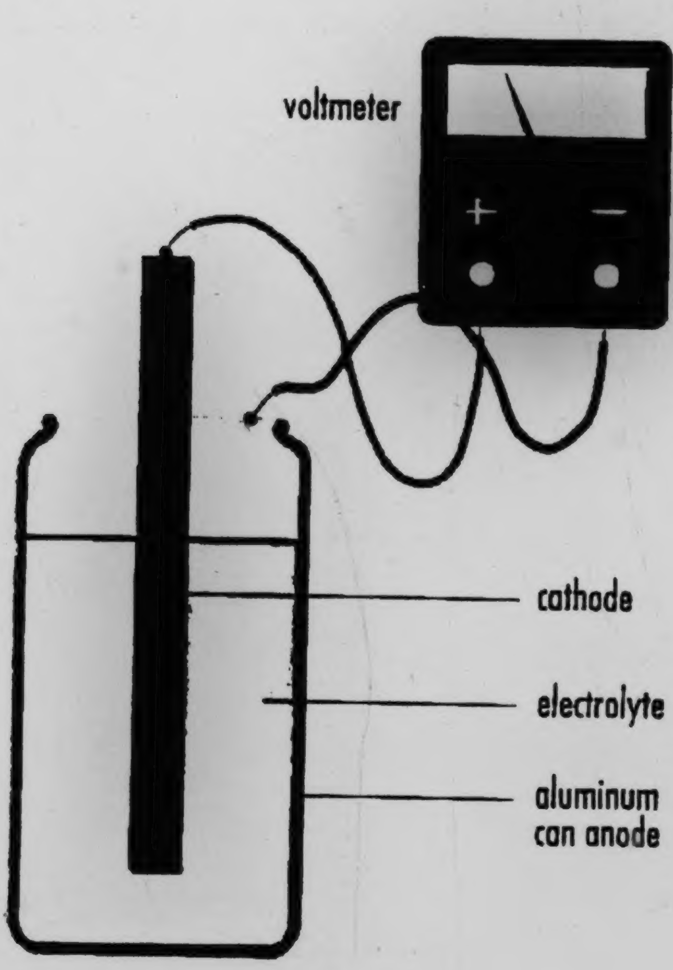


Figure 11. Pop can cell.

Entering the Pop Can Cell Activity

In this section accounts of four student groups' investigations are presented. The first pair of students was Jason and Rami, and the second were Manuela and Viet. Both pairs were from the regular Alberta Chemistry 30 class. The remaining two pairs from the Chemistry 30 IB were Salome and Joanna, and the last pair was Cees and Saskia.

Jason and Rami's Story

Students were asked to bring empty pop cans for the activity. In the pre-lab talk the teacher explained to the class what the activity was about without giving a lot of detail. When I approached Jason's work bench, I realised that he and his partner had already obtained solutions in three beakers. All the solutions were colourless and not labelled.

> Jason: (asked me as I approached and held out the can they had already obtained) Do we have to get three pop cans?
> Researcher: What do you think?
> Jason: I think we will need three because we have three solutions.
> Researcher: Do you know which solution is which?
> Jason: Yes, this is NaOH.
> Researcher: Why do you not label them?

At this stage it seemed that these two students had come up with a strategy for testing different electrolytes and needed confirmation of the steps that they were thinking of taking. Their plan seemed reasonable, and Jason's idea of using three cans was also reasonable. It seemed important to me that they not confuse their solutions; hence I encouraged them to label. This perhaps was informed by my own experiences doing chemistry. With three colourless and odourless solutions in unmarked beakers, it was possible for the students to forget which solution was which. Mrs. Smith came over to see what the students were doing, and in the ensuing discussion she suggested that the students make just one cell. Apparently the student teacher had understood the purpose of the activity differently. These students' understanding of the prompt suggested to them to use three different solutions for their electrolyte, which meant constructing three different cells. For a moment the students were confused:

> Researcher: How do you choose?
> Jason: Well, we will use sodium hydroxide.

Although I tried to probe as to why they made that selection, neither student could say. It was apparent that the student intuitively knew that cells were often made of alkalis. The students disposed of the other two solutions they had collected. As a result of this interaction, Jason and his partner ended up changing their strategy by investigating the electrodes and not electrolytes. First they used the copper electrode in their setup. Jason, having learned from the teacher's comments that it was important for the electrodes not to touch, supported the electrode they were manipulating with a clamp on a stand. This was part of the history of doing chemistry investigations that he had learned from previous activities and that he brought to this investigation. Measuring current raised several problems for all students. They were not familiar with the multimeters and therefore did not know how to set them and what scales to read. By playing with the instruments and asking questions, they eventually figured out which meter settings to use.

> Jason: (shouted with excitement to his partner) Oh, look! I got it to work!
> Researcher: (moved over to see Jason's setup) Wow! That's good!
> Jason: (still excited) What do I do? What do I read?
> Researcher: What do you think? You decide. The green scale measures ohms. What are ohms a measure of?
> Jason: Current?
> Researcher: No, no, ohms measure resistance and not current. You want to measure current. The black scales are DC and AC. You want to use the black scale. (The interaction was joined by the other researcher and the

teacher, who jointly helped the students to figure out what their meter reading was. By sharing the meter with the adjacent group and helping them connect it, Jason realised that he and his partner had a much higher reading than the other group had.)

Jason: (felt a sense of accomplishment and bragged a little to the adjacent group) I figured it out first and got a higher reading. I am not so dumb after all. (Their second setup using a carbon rod as the electrode gave a much higher reading than the previous one did. This heightened the excitement and brought about relief. This was their best cell, Jason decided.)

Several things are worth pointing out. The first is the understanding that the students brought to the activity prior to inviting any of us to observe their activity. Their interpretation of the problem was sufficient to start solving the problem, but a small technical obstacle resulted in their changing their approach. Having engaged in the iodine clock reaction open-entry activity and the discussions thereof, the students knew that there were several different approaches to these activities. They later realised that they could have proceeded with their initial approach and that both approaches were sufficient. Their solution co-emerged with the investigation. Each step involved taking risks and making decisions that could probably, in their words, make them "look dumb or smart." Enacting their understanding and engaging in the activities is about them and involves self-referencing. Jason, for instance, saw the success that they experienced as an evaluation of his capability. He was overjoyed and relieved by the consistently high readings they obtained with the different cells they made. This boosted his self-confidence because it meant that he could create a valuable product within this community of knowers.

Manuela and Viet's Story

To start the activity in the lab, Manuela and Viet collected some of their materials from the front bench. At the start they had one Coca Cola can, leads, a multimeter, three beakers of solutions, a funnel, and an ammeter. Viet, who had brought a multimeter, approached the teacher:

> Viet: Which settings do we use?
> Teacher: DC volts (pointed to that setting) measure volts. (turned the dial to illustrate what he meant) So maybe you want to start low, say, about 2.5 volts. You can then change it to amperes if you want to check current.
> Manuela: Excuse me. I have a question. Do we have to get each one of these things, put it in there, mix it with whatever solution we need or --- ?
> Researcher: It depends on what you decide to manipulate. You have the option of manipulating electrodes, say, starting with copper and changing the electrode to carbon and stuff like that. Or you can choose even to change the electrolytes.
> Manuela: No, we are changing the electrolyte. I think that's what we want to do. (turned as if to confirm with Viet) Yeah, we are changing the electrolytes.
> Researcher: Okay. So for your design you can choose to have, say, three cans for how many electrolytes you are using
> Manuela: How many electrolytes are we using?
> Viet: Three; let's use three.
> Manuela: Okay, should we get two more cans? We need three cans.
> Researcher: Yes, perhaps you can have three cans, clean them up, and have your electrolytes ready. Do one, finish it, do another, finish it, and so forth.
> Manuela: Okay, we will do that right now.

Their problem entry strategy using three solutions was similar to the one Jason and Rami initially had. Having been part of Jason and Rami's interaction earlier, which I felt shifted the students' attention perhaps away from their initial intuited approach, I was careful and wanted them to follow their ideas and test them. I was able to reaffirm the students' initial inclinations, which perhaps encouraged them to listen to their intuitions. Encouraging them in this sense, I also suggested how they could possibly organize their activity and be efficient.

How Do Students Make the Cell Workable?

Both Manuela and Viet decided to test electrolytes. Having set up the basic circuit, the students had to be sure that their setup worked. When the setup worked, electricity would be produced, so they had to indicate that their cell was actually producing electricity. Because they also had to compare the cells and decide which cell was the best, they decided to use a multimeter. In using this Manuela made contact to complete the circuit and to test their cell using the leads they had connected to the multimeter. The red probe touched the copper strip and the black touched the side of the pop can.

> Manuela: (exclaimed sarcastically) Perfect!
> Teacher: So what are you thinking now at this moment?
> Manuela: The electrolyte is wrong!
> Teacher: The electrolyte is wrong?
> Manuela: It didn't give us anything.
> Teacher: It didn't give you anything?
> Manuela: (to Viet) Lower the thing a bit. (and pointed to the multimeter)
> Teacher: Turn it down there. (refers to the multimeter scale. Manuela turns the multimeter dial and tries again to make contact.) Try to make contact on the top there, not on the point. You are not getting any reading at all.
> Manuela: (emphatically) No!
> Viet: Try flipping the thing. Maybe we got it wrong.
> Manuela: Even if we switch (he switched the probes/leads so that this time the black touches the copper strip and red the pop can). No! Let's try something else then. (he put down the probes, lifted up and removed the copper strip from the solution in the pop can)
> Teacher: So what could possibly be going on?
> Manuela: It's either the acid is too dilute or it's not working.
> Teacher: So what are you going to try next?
> Manuela: We are going to use NaOH, I guess.
> Teacher: Okay. (left the group briefly and then returned). Did you guys get anything this time?
> Manuela: (turned the multimeter dial and picked up the probes that were lying on the bench). We did it. (moved to contact their pop can cell with the probes to show the teacher)
> Viet: Turn it up. (referring to the multimeter dial and stretched to turn the dial to a higher scale)
> Teacher: Oh! Point-two-three or something like that? (The school bell rang and the class ended)
> Manuela: I am not sure. We are not sure how to read it.

Both students seemed to be somewhat confident that their setup would work, and when they did not seem to get a reading with their first electrolyte, they went on to try a different one. In a sense they established through systematic trial and error that their setup worked. Their initial experience with the iodine clock reaction had perhaps taught them to persevere and to look for options. They gradually had become originators of their ideas and actions and tended to find options for themselves. In this instance they successfully got their setup to work on their own, although with this success a new challenge emerged: They did not know how to read the multimeter. With the help of the teacher's and the researcher's interactions, they also learned to use the multimeter successfully.

Salome and Joanna's Story

The teacher described the purpose of the activity, how to use the multimeters, and how to clean the pop cans to remove the enamel coat. Several students brought their own pop cans, and others used those that had been left from the previous class. Salome and Joanna were in this second class. When students came to the laboratory, there were among the materials bottles of stock solutions for the activity at the front bench, large beakers with solutions that had been used by the previous class. Before the teacher or researcher could make note of it, some students had already collected some of the used solution for their activity.

> Teacher: (announced to class) It is best to use the solutions out of the stock bottles because you know for sure what you are getting. We have recycled chemicals here as well.

As the teacher approached Salome and Joanna's group, they had on the bench top a pop can, a multimeter, some wires, a black carbon rod, a copper strip, and another dull-greyish metal strip. Salome was busy scrubbing the copper strip with steel wool.

Teacher: So what have you decided to do?
Salome: No comment!
Teacher: What have you decided you want to do? What is your first problem?
Salome and Joanna: (looked at each other quizzically, looked over to the group opposite them, and then looked at the teacher, and smiled)
Salome: The same as these guys. (pointed to the group opposite)
Joanna: Yes, the same as —
Teacher: And the same is?
Joanna: Electrode.
Salome: We are testing the electrode with, um —
Teacher: Your manipulated variable is?
Joanna: Electrode.
Salome: Electrode.
Teacher: (confirmed) Electrode. Your controlled variable is?
Salome: Um, electrolyte!
Teacher: And your responding variable will be?
Salome: Which is the best cell?
Teacher: And your criteria for deciding on the best are going to be?
Salome and Joanna: (looked at each other, laughed, and shrugged their shoulders. Joanna waved at Salome as if to ask, "Have you thought of that?" They both continued to laugh without giving any definite answer.)
Teacher: The criteria for best—you are going to get back to me on that?
Salome: Yes. No comment right now. (the teacher moved on to a neighbouring group)

With the help of the teacher's prompts with phrases such as *controlled* and *manipulated variable,* he was able to get a glimpse of what the students knew and the kind of problem-solving strategy that they were going to use. This interaction too helped the two students to think through and to put into words a more specific though incomplete description of what they were going to do.

Translating Words Into Action

We often use words in conversation and assume that they have a shared meaning. In general terms this is often the case, but in special settings such as the chemistry laboratory words such as *make contact* acquire special procedural meanings. As the teacher explained to the students, "Well, until you get it to conduct up there, you know you are not making contact." The phrase "make contact" resonated with students' experiences, but for them to translate it into action, they needed further clarification in action with the teacher. The students had set up their circuit and were trying to make contact on the pop can lid with leads connected to the multimeter to test it. In the following excerpt, for instance, the instruction 'make contact' meant more than a slight touch:

> Joanna: (moved and tried again to make contact, lightly touching both probes on the lid a few centimetres apart)
>
> Teacher: When you are making contact, do not just barely touch the thing as if you are afraid of it. Push it on or scrape it with the ends of the probes. The leads may also be problematic in terms of conducting (Joanna got some steel wool and cleaned the end of the leads); particularly right at the end because that's where you are touching. (Joanna touched the top of the lid again) Okay, it looks like you are getting conductivity now.
>
> Joanna: Okay. (stopped making contact, smiled, and lifted the leads from the can. Both girls seemed relieved.)
>
> Salome: Okay. (paused for a few seconds, smiled, picked up the carbon rod, inserted it into the pop can, and reset the multimeter)
>
> Joanna: (sensing now that they were ready to check their cell picked up the probes and touched the exposed part of the carbon rod with one and the pop can lid with the other)
>
> Teacher: Is there some way that you can make sure you get a much harder contact on that one? Because how much you are contacting seems to be making a difference as well.
>
> Joanna: (mumbled softly) Movement; there's movement there.
>
> Teacher: So you've got a reading now. Remember 250 is now 2.5, So you've got to divide by a hundred there whatever reading you get. (left to visit other groups)

This interaction between the teacher and students helped students to develop an embodied sense of what it means to make contact. Their action was tested each time they tried to make contact because they could either get a reading on the multimeter or not. Without this speech-action interaction, the students would perhaps not have realized that they could get their setup to work. Having successfully managed to get their setup to conduct, they were now faced with the challenge of reading the multimeter, which the teacher hinted at as he moved on to help other groups. At times it took several different attempts and interactions to describe in ways that allowed students to know-in-action, and sometimes it took different people to help students develop that bodily knowing and to learn to use the multimeters. In the following instance the researcher went into the students' problem-solving space at a time when they seemed to need interaction with someone. They were trying to determine how to read the multimeter. Because of the multiple scales and the multiple settings, they did not know what their reading was.

> Researcher: Yes, your scale. It depends on that.
> Salome: If it's at 2.5, then it would be — (paused) If it is at 2.5 —
> Researcher: Which scale do you think is best to use? (Both girls moved their fingers on the face of the multimeter, indicating their understanding of what we were talking about as they tried to make sense of it.)
> Joanna: (counted, pointing at the different scale as she did so) One, two, three.
> Researcher: Which scale do you — ?
> Salome: The first one!
> Researcher: Yes, the 250 one.
> Joanna: So we — (she turned the dial)
> Researcher: So it means the reading that you get — No, no. (responded to Joanna's turning of the dial) What I mean is that you can set it there (pointed to their original setting), but when you get a reading —
> Salome: (excitement in her voice as she now seemed to get the meaning of what the teacher had said before leaving the group) You divide by 100!
> Researcher: You divide by 100.
> Salome: That's what he meant! (paused, then quickly picked up the copper strip and inserted it back into the pop can and exclaimed) Forty!
> Joanna: Yes.
> Salome: (tried with the black carbon rod again to confirm their results)
> Joanna: (pointed at the position of the needle) I think it's about 30.

The processes of getting the investigation to work involved taking little steps at a time: working with an idea, testing it, evaluating it, retesting it, re-evaluating it and determining whether the results they were getting would help them solve their big problem. How did the results that students were getting help them to answer their main problem? Having overcome many of the challenges of getting the cell to work and having several cells with which to work, the students now had the challenge of interpreting the results to answer their main investigation problem:

> Joanna: Oh, so we still read it as 25. If we did one, is it all right?
> Researcher: What do you mean one?
> Joanna: Like, we did only one.
> Researcher: You mean electrolyte?
> Joanna: Yes. We did three electrodes with one electrolyte.
> Researcher: That's fine. So you choose your best cell and you explain what you did and why you did it that way and present your evaluation of the procedure.

Students' Creative Pop Can Cell Setups

Cees and Saskia again worked as a pair. Opposite this pair, across the bench, Terrilyn worked with two other male students. Saskia and Cees had already started working on the activity when the teacher approached them. They had a pop can, a dark-blue sticky substance, a carbon rod, and a clear solution in a beaker on the bench.

> Saskia: What should we do to make sure it's not touching the bottom of the can?
> Teacher: You can try it both ways and see. You use trial and error on that one.
> Saskia: It ranges back and forth, and it's going from 0 to 100 and back and back and back. We are just trying to get an average.
> Teacher: Are you on the bottom there or not?
> Cees: No.
> Teacher: Oh, I see. (He noticed the sticky stuff between the rod and the can) So can you take your hand away so I can take a look? So what are you using here?
> Cees: Sticky Tack.
> Teacher: Sticky Tack.
> Cees: We tested it for conductivity, and it is very good.
> Teacher: The purpose of that is to — ?
> Cees: Prevent it from touching the sides and the bottom of the can.
> Teacher: And how did you test to see whether that is working? How could you if you didn't — ?
> Cees: How could I see if the Sticky Tack was working?
> Teacher: Yeah, in place. You tested it before by itself, but when you assembled the thing, how could you test it is working?
> Cees: (touched the black carbon electrode in the can and the blue sticky substance around it with the leads from the multimeter) By checking here.

Teacher: But you are assuming now that it is stopping conductivity between here and here. (He pointed at Sticky Tack and the lid) Except that now you have a solution in there.
Cees: Oh, yeah.
Teacher: So you could do both tests. Maybe!
Cees: Perhaps.
Teacher: Yeah, to see whether or not it's in fact working in place. I guess you know it's not touching the bottom because of the weight here. (He pointed to the carbon rod) Good enough!

Many students had several challenges in getting their setup to work. These included getting the pop can to conduct, holding the electrodes in place so that they did not touch and short their cell, and learning what it meant to make contact, which included ensuring that the metal was clean and exposed to allow a flow of electrons. Different students solved these problems in different ways. Some students used masking tape to separate the electrodes. A variety of creative ways of using the tape were displayed. Some students used clamps, whereas still others used Sticky Tack or just held the electrodes between their fingers. In Cees and Saskia's case, the Sticky Tack that Cees had brought was used to separate the electrodes and keep the electrodes in place. This technique presented challenges. They had to test it at the beginning to make certain that it did not conduct. Their reflective notes speak to the other challenges that the Sticky Tack presented. For instance, in Saskia's note she wrote

> It was tricky to stick the blue sticky stuff around the mouth of the pop can without letting it fall in, and then putting the second electrode into the can without pushing the blue sticky stuff in. As well, it was a little bit challenging to make sure that the electrode was at the right depth in the can that it was not touching the bottom, but also that it was submerged in the hydrochloric acid. Then it was also challenging to put enough pressure on the cathode with the voltmeter probe so as to get an accurate reading without pushing the cathode in any further.

Even though in his comments Cees mentioned the same problems, he did also mention that it was a good idea to use it. A few minutes later the researcher visited the group. Saskia and Cees were trying to figure out how to read the multimeter.

> Cees: Why here? (he questioned Saskia's setting of the multimeter)
> Saskia: Because this is the only one that has 2.5 to the power of 10.
> Cees: And you move the decimal places over twice.
> Researcher: Yeah I think you've got it right.
> Saskia: What I am reading is ninety on the two hundred and fifty scale equals (she pointed on the meter dial) over (2.5) two point five. That is where we have our dial. That is what we are measuring, right? So that is like moving the decimal places over two because we now get 0.90.
> Researcher: What was the cell combination there?
> Saskia: Hydrochloric acid with carbon.

At that time these students had developed a knowing how-to-use the multimeter that allowed them to describe it to the researcher. They had, however, experienced a problem with their results that they wanted to explain to themselves. They therefore embarked on a journey to find an explanation and a theory about this chemical phenomenon.

> Saskia: For the last ones we didn't get any readings at all but for the first few it was working. Could it mean that the cell had reached equilibrium because there were too many ions in solution or whatever?
> Teacher: If it had reached equilibrium it would be dead. If it shorted out.
> Cees: But if it's dead there wouldn't be any current.
> Teacher: Equilibrium is a good hypothesis but I don't think so because essentially your can would have to be eaten away before you reach equilibrium.
> Saskia: Oh yeah. But we weren't getting any readings.
> Teacher: Something else must have been happening. You can suggest in your write up some other kinds of things that might have happened. For instance, where do you think the research would continue from this? So the problem you are experiencing right now would become another research problem. You have to solve that problem before you can solve the original problem and that's the reality of research.

The teacher was always prodding, asking questions, posing scenarios that required students to extend their thinking beyond the immediate problem. He also tried to get the students to think about the process of research in science at each stage and to think of alternative possibilities in trying to solve or explain the problem. In other words he tried to invite students to shift attention from a one-answer mode of approaching problem-solving to opening their eyes to the many possible routes and answers.

In this activity, initially the teacher took time to clarify the nature of the activity, pointing out that students were to empirically determine which cell was the best. A significant amount of time was spent also explaining how to use the multimeters. For one of the classes, one of the students had previously called Pepsi to find out what kind of coating they used on their cans. So the teacher suggested they use acetone to remove the coat. Time and again the teacher and I had to remind students about the coat especially on the lid of the can. We also had to remind students not to "short" their batteries so that they had to keep their electrodes apart. Different successful and creative procedures and setups that students were proud of emerged in this activity which a recipe type activity could not have exposed to students. Students learned that in science there was not one answer, not one way but many answers and many ways to solve their problems, a realization that may speak to pedagogy and epistemology of science.

Evaluating Students' Pop Can Cells

The pop can cell activity was not only about making a procedure it was also about making a product that could potentially be used. Students had to evaluate both procedure and product. In their reflective notes students could write about how they felt about their experiences in this investigation, what they think they did right or what they think they did wrong throughout the process including in the pre-lab preparatory phase. They could also evaluate their products.

One student wrote:

> This lab was rather interesting to do. I know I learn (and have to think more) when we do labs without a given procedure however I also worry more about making mistakes. Doing this lab was a good learning experience. My lab partner called Pepsi's 1-800 number to find out what kind of a lining they put inside the cans. Other than that we worked together to formulate a procedure which we made changes to, due to lack of time while we were doing the lab. I think I learned a fair bit about voltaic cells and can now sort of visualise how they are set up and work.

This student's comments highlight several pedagogically interesting points. It is interesting. It is a good learning experience and allows him or her to think more. Students' experiences of engaging the pop can investigation were positive despite the frustration that arose from not knowing how to use some instruments or how to get the set up working. Their reflective notes spoke to their emotional as well as their pedagogic challenges and successes. The reflective notes not only corroborated my observations of interactions but also my interpretations of most of the interactions. The notes tended to point to what they learned about batteries and what they learned about their doing and making of the pop can cell. As well students expressed what they felt during their experiences.

One pair of students found a creative way of dealing with multitasking. Depending on how they set their pop can cells up students found that they required many hands to either hold electrodes in place separated and touching the electrolyte and also to connect leads to the multimeter. This pair of students' brilliant ideas and acting-in-the setting not only freed their hands for easier manipulations but also eliminated the potential problem of the pop can lid not conducting. They punched a small enough hole through the lid to hold one of the leads. This worked well for the students and they were very proud of their setup. In their laboratory report they used elaborate diagrams to describe how the set their cell up (see Figure 12).

In Johny's evaluation he wrote:

> The whole experiment was executed smoothly especially with my aluminium-can design that was efficient and effective. A major feature of our design was the small hole used to place the negative electrode of the voltmeter; this allowed the experimenter to have one free hand while the other hand held the positive electrode to the carbon rod. Another feature of our design was the use of masking tape to line the drinking hole to prevent the cathode (carbon rod) from contacting the anode (aluminium can). The use of masking tape to create "tabs" on the carbon rod was a feat of ingenuity thought up by another lab group. To see an actual voltage reading coming from such a simple aluminium-can cell design was quite exciting. Our lab group wanted to continue experimenting the cell using different electrodes but because the class on the day we did the lab was shortened (a Friday) and also because we helped other groups with their design and execution of the lab, we were not able to further experiment.

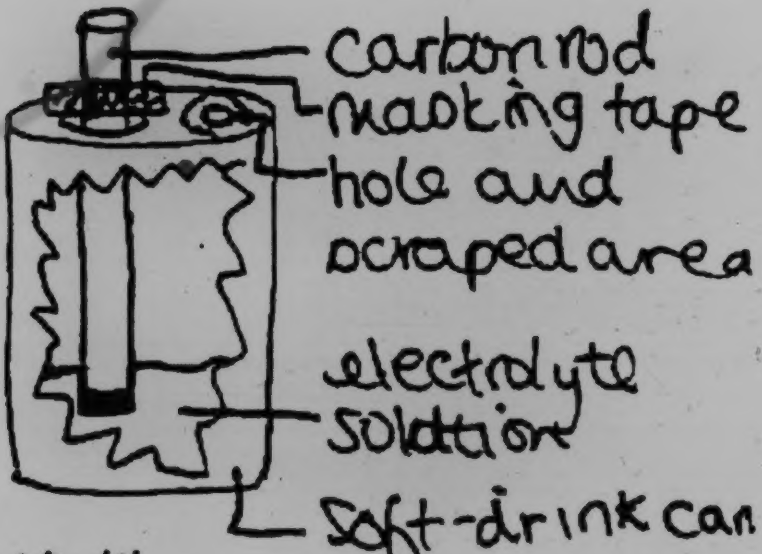


Figure 12. Johny and Kate's pop can cell.

This pair's results reflected that they tested three electrolytes using the carbon rod as the other electrode. With sodium hydroxide solution as their electrolyte they obtained the highest voltage a result that perhaps allowed many to see the commercial used of alkaline batteries (A complete copy of Kate's laboratory report is in Appendix C).

The activity was seen by many students as a creative activity although some mentioned a desire to have more materials or do more tests. They were proud that not only did they learn about the cell but they made one from inexpensive material. "With this experiment, I was able to determine that a battery is in fact very easy to construct. A typical battery that is found in stores is far more expensive than what it is initially worth." They had learned in a more personally meaningful way something closely related to their everyday life. "It was interesting to make our own batteries." Another student's experience suggested that he realized that there were other ways of doing this activity although he did not realize it before. "I enjoyed the lab, but did not understand we had such freedom and could be creative. If I had understood that I think it would have been far more fun, and far more intellectually stimulating." Some students learned about themselves and that their contributions made a difference in this community. One student said, "This lab was fairly straight forward and it was fun to figure out how to solve the problem ourselves and actually got an answer. The use of the voltmeter was frustrating at first until we figured it out with some help. I was glad... in helping to solve the enamel problem." Students had to determine which cell was the best among the cells they had created and they had to say why.

A careful look at what students thought of the activity suggests that some students were still struggling with making the transition from traditional laboratory activities to the less structured and more evolutionary open-entry type of activities. For instance, one student mentioned that they had a problem when they tried to come up with a prediction. In his own words he said, "We felt lost because of lack of assurance as to whether we were doing the right thing and having a valid prediction." This step was not essential in this investigation. Students also learned from each other and appreciated what other students had done that helped their investigations.

Initially some students thought that this activity was difficult but after doing it they thought otherwise. Their remarks suggest that they became more self confident as the activity progressed. A major challenge expressed by students was using the multimeter. This created time pressure as many could not figure out fast enough how the multimeter worked. Some of those who did complained of inconsistent readings. All students thought the activity was reasonable, some thought it was fun although at times frustrating because of lack of familiarity with the instruments used. No student expressed dissatisfaction with the activity. All students seemed to have been challenged. Many students' comments and evaluations connected what they did to what they now can visualize about batteries.

CHAPTER EIGHT

THE ELECTROPLATING ACTIVITY

In this chapter I present the third open-entry activity which was the last in this series. For interactions during the investigation, the chapter uses transcripts from three groups and focuses on the ways students related and communicated and how they translated what they knew and whatever instructions had been given into an investigation. The transcripts are interjected with my interpretations and comments, for instance, of how theory and action interplayed in students' interactions or how students negotiated space or procedure. Following these is presented some of the students' immediate reflections followed by a story of my own engagements.

Like with the other two open-entry investigations, the students were given handouts and asked to prepare a day or two prior to the investigation. They had to design their own problem solving strategies. Some students brought their preparatory notes to class. Many brought small gadgets to electroplate including old coins and keys.

The Electroplating Activity

The third open-entry investigation was carried out towards the end of the electro-chemistry unit. It involved designing a procedure that could effectively electroplate a small object such as a key, a key holder or nail. The investigation is described in the textbook used for the IB program as Investigation 16.8, Copper Plating (Jenkins, van Kessel, Tompkins, & Lantz, 1996, p. 691). The purpose of the activity given in Jenkins et al. was to determine the best process for plating copper onto various objects (see Figure 13). In our study, we modified it so that students were required to determine and write up the best procedures for plating copper onto the various objects they provided. Students brought different items including berets, tweezers, scissors, keys, key holders, spoons, small connectors, old coins, and floppy disks. Students were expected to evaluate both the process and the product and they had to determine the criteria to use for the evaluation.

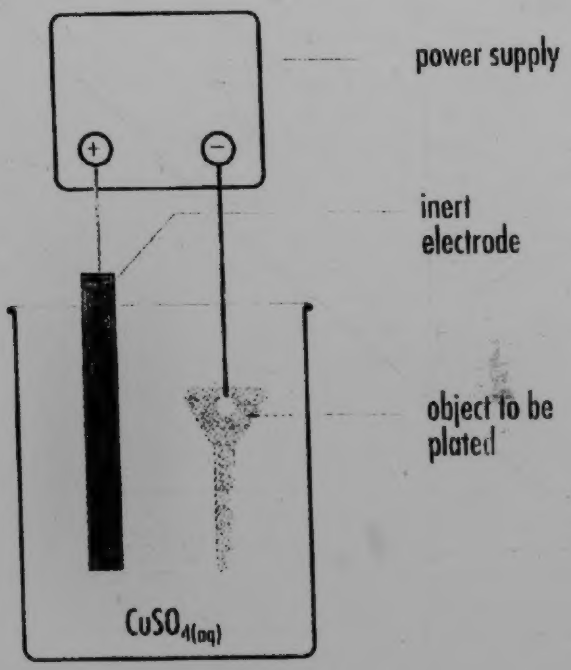


Figure 13. An electrolytic cell for copper plating.

The pre-lab talk for this activity focussed on establishing the nature of the activity in terms of its process orientation. Emphasis was made on the fact that the students would determine what variables were significant for the activity, what variables they were going to control and what ones they were going to manipulate. Some students worked in pairs.

The setup was described with the help of circuit diagrams on the chalkboard and in the text book. The talk also focussed on connecting circuits focussing on series (for ammeters) and parallel (for voltmeters) circuits. The circuit diagram provided in the handout is given below.

Due to time pressures and preparation for the IB and Alberta diploma test, the activity was scheduled for the last day of classes. Both classes were informed ahead of time about the activity and asked to bring small metallic items to plate. The two classes were scheduled on this day one after the other in the regular school time table. To the teacher's and my surprise students from the second class came in with the first class. Given that they were not obligated to come to school this day the number that turned up about 32 was quiet impressive. So we ended up with some large groups of five or six comprising students from both classes. The teacher gave a 10-minute talk at the beginning; all students except four or five crowded around the chalkboard listening to the teacher's presentation in the lab.

Meaning Making in the Electroplating Activity

To explore students' meaning making with the electroplating activity, three student groups were selected. These groups comprised: an all female group with Becky and Liz and an all male group with Alex and Ubbo both from the regular Alberta Chemistry 30 class. The third group was a male-female group with Cees and Saskia, from the Chemistry 30 IB class.

Validating Problem-Solving Ideas

In this excerpt Becky and Liz were trying to make some sense of the assignment. At the opposite side of the bench, facing them, were two male students (Tom and Fred) also engaged in this activity. Having collected voltmeters, connecting wires, ammeters, electrodes and the copper II sulfate solution Becky and Liz started the activity. Their initial setup was a direct representation of the illustration provided on the lab hand-out and the textbook, with only two connecting wires. Conversations took place within groups and across groups, with the teachers and researchers alike.

> Liz: We measure --- like we have to find out how much this weighs.
> Tom: You do?
> Liz: Because then you could determine how much plating you have put on there.
> Tom: Really, really?
> Liz: Well it is a better indication then, I guess. How do we put it in series then? There are only two wires.

The students soon discovered that they needed more wires to be able to use the other pieces of equipment and Becky went to the teacher to find out where extra connecting wires were and collected them. Meanwhile Liz and the researcher chatted about the activity.

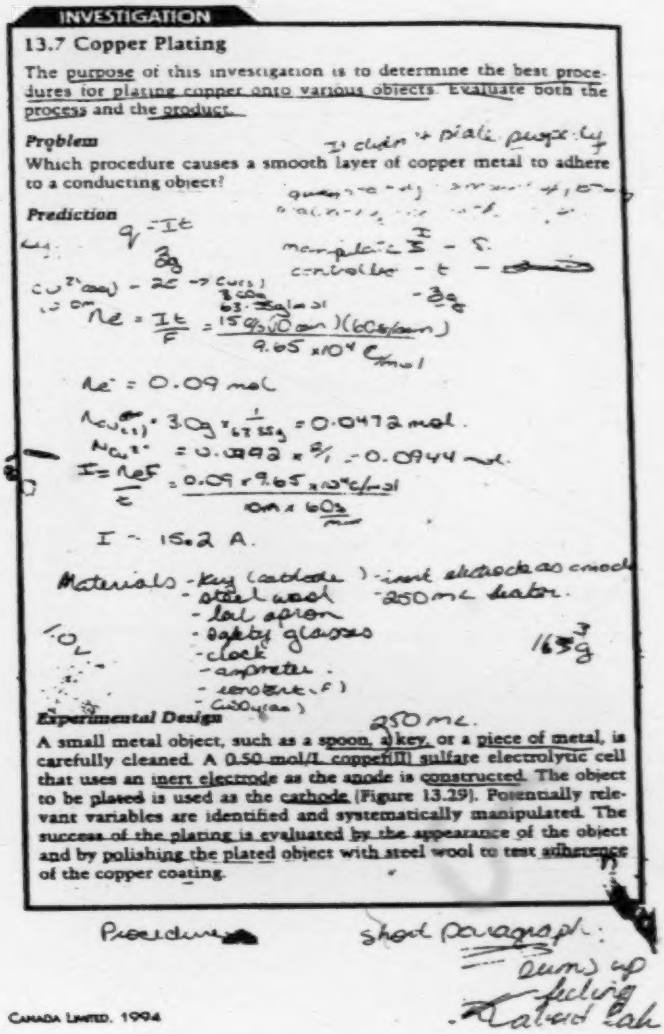
> Researcher: So, Liz what do you think you ---
> Liz: I have no idea. I am lost.
> Researcher: So are you just trying out something ---?
> Liz: I'm lost, I don't even know what I am doing. I am lost.
> Researcher: In your pre-lab what were you thinking of doing?
> Liz: Well, (she pointed at the calculations she did to prepare for the lab) I know I have to put 15.2 amps but I don't know how to set it up or do whatever we are supposed to do.
> Researcher: Did the diagrams that Dr. M drew help a little?
> Liz: No, no.

Liz approached this activity from a theoretical stance. The class had just covered a section of the theory on half-reactions, where amount of metal deposited or dissolved from electrodes could be determined using Faraday's law. By knowing the current used, how long the electroplating runs and the moles of electrons required per mole of product in the half reaction, students could calculate the ideal mass of metal expected to be electroplated. So in her preparation she used that information, as she understood it, to determine a number (15.2 amps) that she thought she was supposed to "put" somewhere. She kind of knew that with her approach they needed to weigh some thing as an indication of how much copper plated and she started off talking to Tom. This brief interaction was perhaps for her an act of validating her initial ideas.

In this interaction between Liz and Becky, Liz had taken a portion of the theory they had learned in class without understanding both its practical implications and the practical implications of the problem situation and created, perhaps, a traditional starting point for herself. Although the students never used Liz's pre-lab notes (see Figure 14), in working with the objects and interacting with her partner she came to realize that the background theory she started with could not help them solve the problem. A different way of making meaning in the laboratory was brought forth.

From Bodily Contacts to Gestures to Language

Becky started connecting wires to the ammeter, stopped to figure out if the connection was right and seeming unsure, plugged them out. Liz took over the wiring while Becky bent over, picked up a pen and a piece of paper, and sketched a circuit that the two later on used to try to figure out how to proceed with the wiring. The group opposite was trying to connect their circuit using the descriptors series and parallel. They could both be seen and heard by Liz and Becky.



INVESTIGATION

13.7 Copper Plating

The purpose of this investigation is to determine the best procedures for plating copper onto various objects. Evaluate both the process and the product.

Problem

I: clean + plate properly

Which procedure causes a smooth layer of copper metal to adhere to a conducting object?

[illegible]

Prediction

$q = It$

3g

manipulate I - 5.

controlled - t -

- 3g

$Cu^{2+}_{(aq)} + 2e^- \rightarrow Cu_{(s)}$

3.00g

63.55g/mol

$n_e = \frac{It}{F} = \frac{15\,C/s\,(10\,min)(60\,s/min)}{9.65 \times 10^4\,C/mol}$

$n_{e^-} = 0.09$ mol

$n_{Cu_{(s)}} = 3.0g \times \frac{1}{63.55g} = 0.0472$ mol.

$n_{Cu^{2+}} = 0.0472 \times 2/1 = 0.0944$ mol.

$I = \frac{n_e F}{t} = \frac{0.09 \times 9.65 \times 10^4\,C/mol}{10\,m \times 60\,s/min}$

I = 15.2 A.

Materials
- key (cathode)
- steel wool
- lab apron
- safety glasses
- clock
- ampmeter
- [illegible] (F)
- $CuSO_{4(aq)}$
- inert electrode as anode
- 250 mL beaker.

1.0 L

163 g

Experimental Design

250 mL.

A small metal object, such as a spoon, a key, or a piece of metal, is carefully cleaned. A 0.50 mol/L copper(II) sulfate electrolytic cell that uses an inert electrode as the anode is constructed. The object to be plated is used as the cathode (Figure 13.29). Potentially relevant variables are identified and systematically manipulated. The success of the plating is evaluated by the appearance of the object and by polishing the plated object with steel wool to test adherence of the copper coating.

Procedure

short paragraph:
sums up feeling
- related lab

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Figure 14. Liz's pre-lab notes.

Liz: No, but if you go like this, you go like this, then you go like this (connected wires to the ammeter and unhooked the one already connected to the carbon electrode, which she held up) right and then you hook this on to this (she pointed to the power supply).
Becky: But then we are supposed to go through ---
Liz: (quickly realized the need to include the electrolytic cell and connected the wire back onto the carbon electrode) Oh, then you go like this and then hook the other one like this. Where did I put the other one? Then this one here and then the other one (she connected the voltmeter in series).

The two students seemingly did not have the technical language of science but as they interacted with the objects, gesturing and communicating with other members of this classroom community in their everyday language they gradually started to make embodied distinctions about the different components of their set-up, i.e., the electrolytic cell and the voltmeter. Having marked the components they could then give them names and start developing a symbolic language for themselves.

Language of Science: A Challenge

As human beings, our structural coupling occurs not only in action but also in languaging. What we say and do act as triggers for others we live with. To be able to make sense of our world and to bring forth our worlds of significance with others we need to communicate our thoughts and ideas. In an action-packed laboratory environment, where students and sometimes teachers and researchers are not sure of what would happen if and when the direction of an investigation changes, how do you communicate the sometimes unclear thoughts and ideas that emerge on the spot while doing something? How do you transform these unclear thoughts and ideas into something you can work with and investigate?

These open-entry activities required students to communicate their thoughts and ideas to each other and to the teacher or the researcher. Often in its infancy, an idea is not easy to communicate clearly because the language of describing it is not well thought out and established as the ideas evolves. To bring it to the point where it can be shared verbally, it may be mediated by some action. In these activities, students demonstrated an initial lack of technical language to describe their process but gradually improved as they started learning and using the different objects and instruments. The example of Becky and Liz in the electroplating activity shows how their language gradually developed from "we connect this to that" to "we need amps here, where is the ammeter." Through connecting this to that and actually handling objects during the interaction with others they got to learn the technical language. Examples of this were found in all three investigations.

> Becky: (moved over to inspect the setup, pulled out some wires, connected the voltmeter and switched other wires) I think this is in series.
> Liz: Isn't that good? Why? Because this goes to that and that goes to this.
> Becky: I think we have to change.
> Liz: Isn't it (the voltmeter) supposed to be in?
> Becky: It is supposed to be in parallel, for a voltmeter ---
> Liz: I don't know what series is. I don't know what parallel is. I just know that this stuff has to be there.
> Becky: Physics?
> Liz: (both laughed) No. I am only in twenty! (By twenty she was referring to the junior level physics course)
> Researcher: So, what are you trying to figure out?
> Becky: How this is going to work.
> Researcher: Okay. Is it connected? Are you trying to connect it in series or in parallel?
> Liz: She said parallel, so I am assuming it is in parallel. I have no clue.
> Researcher: The voltmeter has to be in parallel according to the experiment.
> Liz: I don't even know what parallel is. So, I am completely lost.
> Researcher: If you were going to connect something in series, say for instance you had your power supply there, and if we said the ammeter should be in series, it should be a continuous circle, you would then have your plating going on there. So, if the electricity can go right round the circle, then it is in series. To use the voltmeter it should be parallel to the circuit that you already have.
> Becky: Like it is here. Here, this is a complete circuit to the voltmeter and it is also a complete circuit here. They are not included together.

Liz: (brightened up) Ahh!
Researcher: Then the voltmeter is in parallel and the rest of the circuit is —
Liz: So it means it is going to work now.
Researcher: It should.
Becky: It's working.

In this episode, the students evidently came with different histories to the activity. Their initial actions were very tentative, as they tried to figure out what it was they were doing. They were willing to take risks. Liz, for instance, made it no secret that she did not know what she was doing. Of course this disclaimer did not mean that she could not recognise a connecting wire nor realise that she had to set up a circuit. She did not know what it meant to connect parallel and/or series circuits. She might not have known which terminal was negative or which was positive. However, she went on to start exploring and manipulating the pieces of equipment doing what she understood the activity required of them, "I just know that this stuff has to be there". To portray her initial lack of understanding of the situation at the point in time she repeatedly said "I am lost" symbolising her relation to her environment in that given moment. Her physical engagement and talking through with other participants opened up possibilities for her. To know or to understand was to find herself or her way around, to organize herself. The circuit diagrams drawn by the teacher seemed to be meaningless to her. She was not able to translate them into action until she together with other participants started manipulating the equipment, talking about their actions and making sense of it in the given context.

Becky's actions as well were tentative although she seemed to bring a different understanding to the activity. She seemed to have some knowledge of series and parallel circuits, of the difference between voltage and current and she could even draw her own circuit diagrams which she used to navigate her way around as she made sense of the activity. How did these two histories play out in the progression of activity?

The meaning making emerged as they started to engage in the activity, the actions of one triggered the other's questioning and further actions. There was no single leader or interpreter in the group. They both asked questions and shared their ideas as they went along. There was a certain element of trust and collegiality as they worked together at times each taking turns trying something out, seeing if it worked and then letting the other also try out their idea. The students' confidence seemed to grow as they started overcoming the little challenges and went on to take more risks. With the assistance of a more experienced adult working beside them, Becky and Liz were able to come to an understanding of what connecting a series and a parallel circuit meant in and by engaging the activity. So "it should work," Liz commented. It was evident from this episode that the relationship established in this group was necessary for understanding to develop. Did the proximity of the two groups, who from time to time engaged in brief conversations trigger off certain actions and thought processes? It was apparent during the investigation that the actions and conversations of the two male students in the neighbouring group influenced what Liz and Becky did. In the beginning Liz was talking to Tom, one of the male students near by, about measuring how much copper was plated and also about series and parallel circuits. Although Liz was clear from the beginning of the conversation that they needed to measure the amount of copper plated, she however, did not seem, at that moment, to be concerned about parallel and series. Her interest in these concepts emerged as the male students started talking about it. As Becky picked on what Tom and Fred were talking about, Liz mentioned that she did not even know what parallel was and what series was. So the girls started figuring out what those concepts meant in-action. Our doing is an expression of our knowing (Maturana & Varela, 1987).

The histories, structures and action-speech-thoughts of the students and other participants significantly influenced the nature and direction of the activity. In this activity where some students made limited sense of the circuit diagrams presented in the pre-lab talk, what is adequate conduct? How did the students translate this limited knowing into action to come up with viable solutions? As the students interacted physically, intellectually and emotionally with phenomena in the setting and talked through their enactions, sometimes negotiating course of action, an understanding of what the circuit diagrams translated into within the setting co-emerged with their activity. The initial hesitancy evolved into confidence as the students took risks, immersed themselves and found their way around with others working besides them.

Negotiating Procedure

Ubbo and Alex worked as a pair. When the teacher approached them, the two male students had collected: an ammeter, a voltmeter, a resistor, several leads, a small red voltage step-down adapter, a beaker half filled with a blue solution, and a carbon rod. Some of the leads were connected to the ammeter and others to the voltmeter leading both to the carbon electrode and the other crocodile clip electrode with the key. The resistor was not connected to this initial set up. Ubbo plugged in the power adapter.

Alex: We don't need this right now. (Alex took the resistor, put it aside moved the rest of the connected equipment closer and cleared a working space for them)

Ubbo: Let's start with low voltage. We can change the voltage here (he pointed to the step down adaptor).

Alex: (checking their connections) this looks good. (Ubbo lifted both electrodes and Alex wrote something down on the note pad in front of him. The two seemed ready to start testing their set up.)

Teacher: So what are you guys thinking of trying there?

Alex: We are going to manipulate the voltage. So we will have the key [to be plated] in there first then. We will turn it on. (Alex slowly put the key in the blue solution and then picked up the carbon rod and gently and carefully lowered it into the same blue solution.)

Teacher: Be very careful not to touch those or you will short everything out. (Paused) The voltage is going the wrong way there.

Alex: How?

Teacher: (turned the voltmeter to face Alex and Ubbo) you have something hooked up wrong. If you had this way facing you, you would see the better. I saw the needle going the wrong direction.

Alex: (lifted out the carbon electrode, placed it on the bench as they went through the wires to figure out what might be connected wrong).

Teacher: (noticed something, inspected and touched the leads going to the ammeter) remember your ammeter here has to be connected in series.

Alex: Yeah. It's right here.

Teacher: (followed one of the leads) yeah, except that this is not going anywhere. You have to go to the meter and then from the meter to here (he pointed as he talked). Oh, you have them put it in parallel again.

Alex: We did?

Teacher: Yeah. It's just connected from here to here (he pointed at the two electrodes). The current can go through there or through here.

Alex: Oh, I see (he took some wires apart and tried to figure out how to re - connect them). What do you mean?

Teacher: It has to be in series. (Both Alex and Ubbo removed some of the wires they connected and continued to try to figure out the right connection as they talked to each other.)

Ubbo and Alex negotiated what they were going to do, each student making suggestions that the other student considered and together they set up their first basic connection before the teacher joined them. The teacher's intervention came more as a validation where the teacher saw their setup not working as it should when wired properly. The teacher pointed the students to possible sources of error. The ammeter had to be connected in series while the voltmeter was connected in parallel. Students were finding it difficult to determine what exactly that meant in their setup. The teacher following their leads and elaborating on the flow of current worked as a unit with the students to point out some of the possible misconnections. The students decided to take everything apart and start again so that they could follow the direction of flow as the teacher pointed out. They unhook the old one and reconnect the new one, taking time to ensure they have their "series" and "parallel" connections right. They finally seem to be ready to start plating.

This second attempt seemed satisfactory to the teacher as he followed their connections again.

Persevering

> Researcher: (revisiting the group) your other trial how long had you left it for?
> Ubbo: Fifteen seconds.
> Researcher: So how long are you leaving this on?
> Alex: Sixty seconds.
> Researcher: With the fifteen seconds one did you get some copper plated?
> Alex: No. It did not look like it. (After their sixty seconds was over, Alex took out the key from solution, inspected it, and dried it on paper towel). No change!

The students continued to struggle with the set-up, trying to get it to work but could not get it to work. As the class ended, they cleaned up, put away everything and checked with the teacher.

> Alex: We weren't able to get any results.
> Teacher: No.
> Alex: Our battery produced a little bit of current but the dial changed a little bit when we put it to max.
> Teacher: So you never did get any thing.
> Alex: No.
> Teacher: So how do you feel about that?
> Alex: I kind of feel like trying again.

Although the students did not get their setup to work, they did not give up. They needed to try again at a different time so that they could get results and in a sense get validated as knowers. Ubbo's reflective note pointed to some things that he learned despite not having been able to get their electroplating to work. He wrote:

> Before working on this lab, I have no idea about which variables can make out the best procedures for plating copper. During this lab, the power supply has some problems; it can't give out any voltage in it. After this lab, although I have no idea on the best procedures, but I know voltage, current, object and concentration is important variables.

In the next electroplating story, the teacher decided to give the pre-lab talk in the laboratory. Because previously students had had difficulty with the basic set up, he also set up a proto-type circuit on the front bench for students to refer to when they needed to consult about the circuit setup. In the pre-lab talk the teacher described, using circuit diagrams on the board, how to set up their electroplating apparatus[11]. He mentioned how the voltmeter needed to be set up in parallel and the rest of the equipment in series circuit. Both Alex and Ubbo struggled with setting up these circuits although they seemed to understand the concepts in principle.

Negotiating Space for Action

With the larger class, students made larger groups. Terrilyn worked with Cees and Saskia. When the researcher approached this group, the students had already set up their apparatus with the red 6-12 volt DC power supply connected to the ammeter, the carbon electrode and small object to be electroplated. A multimeter was also connector in the set up. All three students were holding some leads or something else in place with their eyes focussed on the beaker with the blue solution. A blue voltmeter was connected to the set up. Terrilyn plugged in the DC power supply to the bench power outlet as the researcher approached them. "Okay" she said as she looked closely at the beaker with blue solution as if wondering whether they were ready.

---

[11] The teacher, listening to the students' struggles and frustrations, had learned from the previous year two things: first, that he needed to bring the different descriptive representations close to where the students were doing the chemistry; and second, that he needed to present these descriptions in as many different ways as possible. Hence the three different descriptive tools—talk, diagrams, and proto-type setup.

> Researcher: How are we doing here?
> Saskia: Still trying.
> Researcher: Getting any copper plating.
> Saskia: (touched the leads from the multimeter lightly on to the electrodes that Cees is holding in place) Are you sure I am supposed to touch here?
> Terrilyn: Harder!
> Cees: Touch both electrodes.
> Saskia: Are you sure?
> Terrilyn: Yeah, that's a good thing, nothing will happen to you.
> Cees: Move it over to the thousandths, DC.
> Researcher: (noticed bubbles on the key) It's not supposed to bubble.
> Cees: It's not supposed to bubble.
> Saskia: Gross! Do you see that? Why does it happen? (she noticed a black deposit in the beaker)
> Cees: Do you want to hold the black one?
> Saskia: No I don't (firmly with a serious face).
> Terrilyn: (stretching her arm to reach out) this one?

The manipulations in this activity were challenging and sometimes confusing for the different groups because of the many connecting wires and perhaps the many instruments student selected to use. Agasta wrote in her reflective note, "the lab wasn't too bad, the only part that was confusing was setting up of the [electrolytic] cell. There were a lot of wires, but once that was straightened out it was alright. The actual plating was not difficult." In Cees, Saskia and Terrilyn's investigation they had made a setup that needed at least two people working together as a unit to make their investigation work. Working together trying to separate and keep in place electrodes while at the same time trying to make contact with the multimeter created a challenge where students had to negotiate their space for acting as a unit.

Leading the Investigation

Cees: Yes. What ever you do, (pointing) don't touch this one at the same time.
Saskia: Are you sure its plating?
Terrilyn: Yeah I can see it (she lifted the key out a little)
Cees: Lift it out let's see.
Saskia: Oh cool! Put it back in.
Terrilyn: Is it making hydrochloric acid? What is it? Is it copper chloride?
Cees: Yeah, the blue colour is copper chloride.
Saskia: oh - copper two ion! I see.
Cees: Let's turn the key to face the other way so it plates on the other side. (Terrilyn moved to turn the key).
Saskia: Get the wire out of the way.
Cees: (circling his index finger a few times) No, no, this way. Look the way my hand is moving (seeing how awkward Terrilyn was holding the alligator clip with the key, suggested) How about you hold this one? (Referring to the carbon rod he was holding which is now closer to Terrilyn) and they switched.
Cees: Move over a little so it won't touch.
Teacher: (teacher came to the group) so what are you guys up to?
Saskia: I know virtually nothing about this current stuff. (She removed the leads from the multimeter).
Teacher: Oh h! What is your initial reaction on the plating process there?
Cees: It's really fast
Teacher: Yeah.
Cees: (to Terrilyn) go and get us a paper towel.
Saskia: So we can wipe it. Will it come off?
Teacher: You can wipe it and see whether you can polish it. So try two things, first wiping and then polishing. What you really want to do is to be able to get some plating that will withstand both wiping and polishing. (Teacher left to visit other groups and returned after about ten minutes.)
Teacher: What have you folks been doing?
Cees: We lowered the power and plated these two (referring to two other brown keys lying on the paper towel).
Teacher: And did it slow down at all?
Cees: Oh it was much slower.
Teacher: Did it do a better job?
Cees: (held the key for the teacher to see) Oh yeah. We tried to polish this off, but with this other one it came right off. This one did not. (The students continued to try other things and discovered along the way that some of the keys became shinier in the process).
Researcher: (visited group about five minutes before end of class and found six keys plated to varying degrees). What voltage are you using?
Cees: twelve volts.
Researcher: Did you use the same voltage through out?

> Cees: No. We used six volts for these (pointing at three shiny brown keys lying on the bench) and twelve for these (pointing at the rest of the keys). The plating seems to be better at six volts.

In this group's interactions several things seemed to be going on. Saskia who seemed not to be too keen on learning about and learning how to handle electricity decided to be an observer, refusing at times to help the other students in the manipulations. Cees on the other hand assumed the role of the group leader. He instructed the two female students on what to do, what to hold, how to hold it when to do what at the same time he seemed to be the one leading the thinking about what to do and where to take the investigation. The teacher's interactions were more in the form of comments that could help shift focus if listened to carefully. Cees in this interaction seemed to be listening to these cues and modifying their action based on the teacher's comment.

With this group, since this was their last day of classes, I did not ask them to provide any written laboratory report. Instead I arranged to interview some of them who volunteered since the interviews could only be outside regularly scheduled class time. Some were interviewed individually and others with their group partners or friends.

The experience from the pop can cell informed us that not many students were familiar with most of the materials used in high school electricity unit in physics. So a relatively lengthy pre-lab talk was presented describing with the help of circuit diagrams, the kinds of circuits to use with the different instruments (ammeters, voltmeters, resistors). In one of the classes, the pre-lab talk was presented in the classroom and the investigation was performed in the laboratory. This separation between classroom and laboratory became a good learning experience pedagogically. Even with the somewhat lengthy discussion about the different circuits and how to set them up we realized that students were not able to translate the information given in the classroom into action.

Where as, with the other two classes the pre-lab talk was given in the lab with diagrams on the board and a prototype set-up on the teacher's bench. This way, students had a model that they could compare their set-up with and get a head start. There were a lot of question about setting up parallel and series circuits. Students did not know-in-action what the two circuits could look like in their set-ups or even why one was preferred to the other in different instances. This lack of familiarity with equipment made it difficult for students to even know how to test whether the equipment itself was faulty or not. Therefore, a lot of the time was spent checking whether the equipment was working or whether the circuits were properly and safely connected.

Students' Immediate Reflections

Ubbo and May were interviewed by the teacher immediately after they completed the laboratory activity session while they were cleaning up. The immediate reflection offered students a chance to give us feedback on how they felt while they were still closely linked to the doing of the investigation. These interviews reflected how the students felt at the time about the experiences they had just had.

Ubbo and May's Interview on the Electroplating Activity

Teacher: So what do you guys think of this lab?
May: It was kind of hard to get ---
Teacher: Would you like to do labs like this or less like this or what?
May: I didn't like this kind because, like there wasn't enough information to tell us what to do and the time.
Teacher: What if you had more time what would you think?
May: May be a little bit, may be just a bit better.
Teacher: But generally?
May: I think they should give us either an experimental design or procedure or both.
Teacher: Okay. (Addressing Ubbo) So what do you think?
Ubbo: That's not good.

Teacher: Pardon.
Ubbo: That's not a good lab (shaking his head and seeming displeased). Time is not enough. That's not enough time to do anything!
Teacher: So which one would you go on the side of if you had more time would like to do more labs like these or would you rather not do labs like these?
Ubbo: (shaking his head in disagreement) I don't like it.
Teacher: You don't like it.
Ubbo: It's not fun.
Researcher: Why don't you like it?
Ubbo: I do so many trials and I can't get the results. I don't like it (shaking his head).
Researcher: Remember the first time you were manipulating more than one variable at once and you had to change to try and manipulate one variable. So probably you didn't ---
Ubbo: Yeah! Some time wasted on that (still shaking his head, seemingly not pleased and looking down).

Emotioning

Our creations are part of us. They are a statement about us. In this excerpt both Ubbo and May were not happy that they could not get the results they wanted. They both felt there was not enough time for them to complete the investigation. Ubbo commented that even after many trials they still did not get any results. The challenge with the open-entry investigations was that sometimes students spent a lot of time trying to get their investigation working. This caused a lot of frustration for those who spent most of the time trying to get their setup to work. Students who managed to get their set-up and the instrumentation to work found it fun. Maureen wrote:

> This lab, I found it to be fun and learning experience. You didn't really know what you were doing at first, but about halfway through you already know what you are supposed to do, and then you start making up ideas and things you want to manipulate and control, and it is up to you. It is your decision. The fun part was you didn't really know for sure if you've got the right copper-plated colour, and maybe you've got the wrong colour, then you knew something was wrong in the connections of the wires. So then you had to start all over again. But at the end we found the right perfect colour.

These investigations that not only challenged students intellectually but also emotionally. The strong negative feelings Ubbo expressed using both his bodily movements (gestures) and verbally suggest that he perhaps saw this experience as a personal failure or as a waste of time. Although he never managed to try it in his reflections and perhaps from discussing with other student and the teacher he learned a lot from his perseverance.

Students' emotioning was inferred from the way students treated the objects. Students seemed to value the little objects they had brought to copperplate. When the copper plating was successful the objects became little treasures or souvenirs that validated their chemistry doing. This also gave students a sense of ownership of their processes. These were their objects they could do as they pleased when they were done with them.

PART THREE

CHAPTER NINE

INTERVIEWS WITH STUDENTS

My experiences with students in these open-entry investigations told me that I needed to have conversations about their experiences in a less time pressured setting. There was more that students had learned about meaning making in chemistry that classroom video-taping of interactions alone could not show. I therefore arranged with students, at their own time, to have these conversations. This would help me glean at some of students' meanings derived through the whole process and perhaps speak to or touch on some of the underlying perspectives that guide the students in their meaning making. I knew that students could not articulate this directly but in the ways they assessed and interpreted their own interactions it could point me to their pedagogical, epistemological as well as their ontological inclinations.

The conversations or interviews allowed students to step back and reflect on the interactions. Their reflections pointed to a multiplicity of levels of reflection which borrowing from Schon (1983, 1987) could, perhaps, be categorized as reflection-on-interaction and reflection-in-interaction. A third categorization that I refer to as self-referencing, could perhaps be the equivalent of what Wong-Wylie (2003) referred to as reflection-on-self-in/on-action (which since we are focussing on interaction could perhaps be referred to as reflection-on-self-in/on-interaction). She described this as the tacit knowing that focuses reflection on and "emphasises salient personal experiences that influences and shape the person of the profession." (p. 10)

Interviews With Students

I interviewed several students separately about their experiences with open-entry laboratory investigations at the end of the course. I was interested in knowing what kinds of impressions students were leaving with regarding chemistry laboratory work, i. e. whether students noticed any changes in the ways they perceived school chemistry laboratory work. Although I interviewed fourteen students, because of the length of the dissertation, I could only use three of the interviews. Although some of the students interviewed chose to be interviewed with their laboratory partners or their friends, the three students whose interviews were selected here were interviewed individually. Many of the ideas that emerged from these three interviews were echoed in different ways by the other ten students interviewed. The three students are named Jager, Irene and Ursula. I present here brief descriptions of these three individuals to paint on canvas a picture of the persons I talked with.

Jager was a quiet soft-spoken male student who seemed eager to listen and learn. He seemed to like to think through issues and would not interrupt class but wait until class was over to address an issue he wanted to follow up with the teacher. He seemed a little reserved and tended to work alone. The conversation with Jager seemed to focus more on specific details of the process of doing and making sense of that doing. Although it shifted from time to time from specifics about the doing (the local dimensions of the research problem) to the overall learning (the global dimension), it tended to emphasize more the local dimensions.

Irene was a relatively quiet female student who seemed busy or preoccupied most of the time. It appeared to me that she was deliberate in her ways of doing things. She took time to think things through. Even during our conversations she took her time pausing to think about the question or the idea presented. She frequently had interactions with the teacher that gave me a sense that she was self-confident. She seemed relaxed in class and always presented neat written work for her assignments. It appeared she spent a significant amount of time on her school work. Her conversations seemed to be biased towards self-evaluation. I was keen to know her views on what we did in chemistry laboratory investigations. However, as the conversations evolved other interesting ideas emerged from these conversations that I could not ignore

Ursula was quite intriguing. She had a kind of brilliance in her eyes that made it easy to notice her presence but tended to be so quiet in class that you could almost forget her. The video clip of her interactions was the shortest of all the prepared clips lasting about five minutes. In reviewing the videos, I found that striking because between the teacher's recording and mine there was very little direct recording her. When she was in the laboratory, unless she needed a piece of equipment or something like that, she was almost totally engrossed in her interactions, sometimes working alone or parallel to her partner. The conversation with Ursula was different from the previous two because she tended to talk confidently at length about the ideas that emerged or that I raised. She was not hesitant to ask her own questions.

In writing about these conversations I chose to write my part in my present role of an interpretive writer researcher, combining the questions I asked with interpretation of my understanding from the enactivist perspective. Although the students were interviewed separately, I present their conversations here as a braiding made up of four strands. The first three strands represent the three students' contributions and the fourth strand represents my contribution which is somewhat different from the others because of its multiple layering. In terms of time my contribution as written here represents my questions, my statements and my exclamations at the time of the interviewing as well as my thoughts and interpretations now. I have written the interviews this way to highlight and braid in the different themes and coherences that emerged for me. All the interviews began with the prepared video-clips of their own interactions.

Observing Self in Interaction

Conversationally interactions begin with ice breakers or starting points which in a sense are meant to invite the other and to create a space in which the other feels comfortable to partake. After watching the video clip our conversation began.

Researcher: What do you think?

Irene: I think, with any of those three or four labs that were required, I think it would have been a lot more organized if we had a procedure written down or if we [my partner and I] had thought of this ahead of time.

Researcher: What do you mean if you had a procedure written down?

Irene: One thing that I found working in a lab last summer is that, if I had a piece of paper with steps that I could follow in order, that I had either thought of myself or were already provided for me, then I could focus on other things and really control variables or making sure that part of experiment was the same repetition.

Researcher: (nodded) mmh!

Irene: I think I see that [as a] continuing problem with my experimental work. Going from a classroom, from what I know in classroom to the lab situation, I find there's a difference in my certainty.

Researcher: Is there a way you can prepare for that, to make sure that all your lab actions are certain? (Long pause). Is there a way, I mean how do you deal with that uncertainty?

Irene: (seemingly thinking deeply). Well —

Researcher: Is there something that you would expect to be there in any lab set up?

> Irene: Well, its not really the equipment but what I'm going in with is a certain, I guess is a certain mind set, what the orientation of what I know is sort of an application of what I already know but just thinking of it in a different way.

Irene's conversation so far seemed to point to a possible bias towards a particular perspective or a particular mind set that influenced her knowing what-to-do and how-to-do. In her own words "I'm going in with a certain mindset ... [a] sort of an application of what I already know." She seemed more inclined to think in terms of using knowledge provided in classrooms and not necessarily creating or testing knowledge, an epistemological stance in which the student does not see herself as a part creator or part originator of knowing. She wanted to be certain of or have a written down procedure before she started the investigation. It appears that in her mind's eye there is a clear separation between reflection-in-interaction and reflection-on-interaction. Her approach seemed to suggest a perspective of linearity where she has to first reflect-on-interaction, carefully laying out a detailed step-by-step procedure she "could follow in order" and then going in to the laboratory and focussing "and really control[ling] variables," a reflecting-in-interaction, perhaps. Students' inclination towards this way of seeing and doing is plausible given the extended history of interactions students have had in traditional laboratory settings where problems, procedures and conclusions are known ahead of interactions and subsequent processes are relatively linear What was Ursula's opinion?

> Ursula: *Well, I guess the last one, there [on the videotape], when Dr. Meulenberg was showing Mike and I how to use a multimeter that's a skill we should have learned earlier on probably. We were never really taught how to use basic instruments. I don't think we got a very good background in that. So, I guess that was a good thing to finally learn from that activity. I think in Chemistry 30 at least we did a lot more labs. [T]here was a lot more emphasis put in doing them right. I learned a lot more labs. Even in the way we wrote them up, especially, like*

> *in the way we wrote the evaluations and stuff like that. I guess the first part you started with some things from the Group 4 project. That was a different experience going to the river and actually doing something. Our labs are hands-on but that was actually going on-site to do something. That was a good experience. I think lots of the tests that we did there, it was awkward at the first doing them in that environment, on picnic tables and stuff like that. But they were fairly simple. It was pretty easy to do them after a while. It was also kind of rushed. It was a little bit disorganised. We all knew how to do the tests, everyone was clear on that. But in terms of actually going into the river where we should take the water samples from, that was a little bit more difficult to figure out.*

Ursula's conversations and opening remarks immediately focus us on the teaching and learning. She seemed to be able to distance herself a bit more than Irene and focussed on the interactions and the activities, telling us what she liked and what she thought was interesting to her.

> Researcher: (paused) If you had a chance to make a change in the chemistry curriculum, what kinds of things would you like to see change?
>
> Irene: First of all I would have experiments where students had to extend their thinking such as the iodine clock lab or the pop can lab. I would say that those labs should be two to one in comparison the one being the verification sort of labs.
>
> Researcher: Mmh (nodding)!
>
> Irene: Although I would not likely pass, I would like to see the chemistry curriculum become broader and involve more. I understand though that there are time constraints in the school year and things like that can't be accomplished maybe but. The electrolysis, section the electrochemistry I mean I would have to learn more extensively. All sections that we have learned, not only this year, but also in chemistry 20, I like to see extended. I would like to see all of that being part of regular curriculum and being taught on a regular basis.
>
> Researcher: When you were doing these activities, which kind forced you to reflect more?
>
> Irene: Do you mean after?
>
> Researcher: Even before and after. Which kind demanded more of your attention?
>
> Irene: The iodine clock lab, close to nothing. I thought about it on my way to the lab. But situations that were new, that I wasn't familiar with, like the pop can cell especially. I thought of how I could use the can and I don't know I still think about that lab actually. I keep thinking about what I could improve and ---
>
> Researcher: What do you think you could have done differently?
>
> Irene: I think I could have come more prepared. What happened was that since the pop can was one of the electrodes obviously the other electrode couldn't

> touch the pop can. But it is strange that in trying to think about that other variables, I forget about that particular variable. I wonder whether it is because I didn't write it down or because I was just rushing it too much or just um - I am not sure what it was. So that's one thing the logic of that I am going to carry away from here, yeah, that and trying to electroplate a plastic disk.

Letting Go of Certainty

From interacting with students in the laboratory, watching the videos and talking to other students about their experiences, I knew that students struggled with the uncertainty and unpredictability characteristic of these complex open-entry activities. Uncertainty existed at many levels of the investigation. I wondered how Irene felt about this. "How certain were you with the procedures that you developed as you progressed through the activities that we videotaped?"

> Irene: Quite uncertain, quite uncertain! I kept wondering whether I was - Well, the first thing that runs to my head is, "Why am I doing this? Why am I holding this piece of lead or whatever? What are we using it for, and how are we supposed[12] to use it?"
>
> Researcher: Mmh!
>
> Irene: I think I am uncertain because I am uncertain about or I have very little confidence in my ability in the lab or using equipment. I think that you can see that in the video, a great deal of hesitancy.
>
> Researcher: but, does it change with time as you do the activity, as you do the lab? (Paused, watched Irene and it seemed Irene was not clear of the question). Do you find that you become more confident or less confident as----
>
> Irene: I think I became more confident with the equipment I had used before. If it's a new kind of lab but the same equipment that I had used before such as in the iodine clock lab, we used the same beaker, same pipette, same solutions but some different kind of experiment, a different way of thinking about it. Then, I am more confident both at the beginning and the end of the experiment. Where as the experiments where there's a new

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[12] Irene's line of questioning herself about unfamiliar equipment may point to her epistemological understanding of science. For what are we using it, and how are we supposed to use it? The term *supposed to* implies external origination of ideas or rule of interaction with phenomena, external to the student. This may be an expectation arising from her long history of traditional laboratory activities.

situation completely, such as a D O [dissolved oxygen] kit, yes there is an increase in confidence as I go along because as you get a result, you may say Oh! Gee I got a result I must be doing something right.[13] Yeah, confidence does increase but marginally, not by much.

Researcher: So you think if you had a second trial, a second go at it? You would certainly be more confident and you would even probably look out for variables that probably in the beginning you would not look out for, rather than just wanting to see it work.

Irene seemed to be critical of herself more than being critical of the process of investigating such as being critical of designs, procedures and skills. Her focus was on her lack of certainty and little confidence in her ability to use equipment or to think logically in the interactions during the investigations. She indicated that her level of confidence changed marginally during the investigation, in the same breath, however, acknowledged that she thought her confidence would greatly increase if she had a second go at it. Perhaps, she felt that she was not prepared enough, a concern that other students also raised. It would seem that this perceived sense of unpreparedness, which comes with uncertain nature of these open-entry investigations pre-occupied her mind.

Irene: (nodding) Right! I would definitely be. I think that's the way scientists have done it in the past because when they had microscopes work! And they worked later to improve microscope—that sort of thing so it is sort of an evolutionary process.

Researcher: In fact its not only in the past even now when you go into new areas like in areas of cancer research, AIDS research there are always new things that people are encountering and they have to find ways of coming to understand them better. [Irene nodded] And then probably with more repetition of tests you start having multiple perspectives of the issue and you can tackle it better once you have different perspectives of the issue that you are dealing with.

I wondered whether Jager's experiences of uncertainty could compare with Irene's. If he did experience uncertainty how did he experience it and how did he handle it in his investigating. So I inquired from him. I am interested in understanding more the process of meaning making in these chemistry investigations. How were you able to make sense of the activities?

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[13] Irene, in the face of success, seemed not to have perceived a significant boost to her self-confidence.

> Jager: First of all I guess from the iodine clock lab the one that I remember most is going in there not having enough preparation done ahead of time. You know, to control all the variables. There are so many variables involved with that lab there that I think as a student you have to take of time to consider them all. Even just in the way that you are going to do the timing from the start to finish. Like I saw in the video there was another student there who had the idea of swirling it so that it makes the reaction to complete itself more quickly. That way you eliminate more of the error of where you stop the timing.
>
> Researcher: But could you realistically prepare yourself for all the variables —
>
> Jager: Well, you can.
>
> Researcher: Or you had to go in there and experience it to know where to start?
>
> Jager: Well, you do have to do the experimentation and decide. Not knowing what the two solutions are you can't fully prepare [for the activity]. You can't say solution A is such and such. So I know I am going to need more [of solution A] than solution B. But I think if I had done a little bit more thinking about just how I'd — (stopped, paused for a little while, seemed to be considering the option, changed his mind about it and continued) Well, even that --- (pitch of voice changed as he seemed to be changing his trend of thought, moved his head side to side as if weighing the ideas that came rushing through his mind and paused) maybe not. Because I guess you do have to go in there first and see how quickly the reaction is going to occur if you just let it sit, or if you swirl it. Yeah, so you do have to go in there not knowing everything. I think even if there hadn't been that much of a time constraint, you might have been — I tried to find a good position to just let it sit and react and then try to find a place [or perhaps a point during the reaction] [14] where I could try and stop the timer every time I try the reaction but it was --- but now in retrospect I can see that there would have been a lot more easier ways I could have done that.
>
> Researcher: For instance? How would you change what you did?
>
> Jager: Well, I think the swirling would have been a good idea. Swirling it around and then have someone else watching it as long as you have the same person doing the timing all the time. Essentially you would have the same error from them. So, you have to have the same person, that would control

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[14] Jager must have struggled with determining the reaction endpoint. His comment about how in retrospect he could have changed what he did points to this. It was interesting that he also thought that the timekeeper could influence the results. Could it perhaps be that he recognized that our histories and our physical conditions influence the meanings we make?

one of your variables having the same person doing it each time and the same person doing the measuring and their judgement is going to be consistent throughout the experiment.

Researcher: What about the other activities?

Jager: For the last one that we saw there, the pop can one, I think we went in there we went in there definitely without having experience of some of those meters. The one we had, had a digital read out and it was a little bit difficult trying to figure out what kind of a reading you were actually getting. And not having enough experience with all the different settings on it was another challenge. Dr. M had a very good idea of testing it with a battery to check it out. You take a known voltage and test that. It was definitely a challenge to try to set up the pop can like initially I first thought it would be a really good idea to put a paper towel all around [the electrode in the can opening] and sort of stuff it tightly in there. And it worked out okay it did not quite hold the electrode in there as tightly as I wanted it. When you make contact with a probe it sometimes pushed it [the electrode] down too far towards the bottom. And, of course, you brought up the point that it might have been touching the bottom at one time which is something you don't always consider right in the beginning. (Pause) Yeah, mostly the equipment there with the multimeters was a bit difficult at first. We tried a lot of the different settings to kind of get orientated as to how and what settings to use.

Researcher: So how did you feel coming into this and finding that here is a multimeter that I haven't used, and where do I start. How did that make you feel?

Jager: Well, it's a bit frustrating because I have had experience with some of them and I felt comfortable using them. And with my background from physics I know that you can start off using ohms to test the conductivity and what not. It is just that on this one there happened to be a lot of multiple settings for voltage and measuring current. So it was a bit difficult because there was a variable one and a standard one. It is a bit frustrating actually because you know when you have the restraints of time and you want to get in there and have as many read outs as you can, as many try outs as you can so you can get good results for your analysis later on when you are going to be doing it. So you - come in there and everything is kind of moving pretty quickly and you want to get moving too, so it can be frustrating. It would be nice to have identified the equipment you would be using before you go in there and how it all operates and what the symbolism used means.

Researcher: You'd like to be more familiar with the equipment before the lab.

Jager: Yeah. A lot of the times the labs that we did this year, we came in there we had Dr. M's outline of the lab sometimes there were materials written there but a lot of the times the materials that we actually ended up using were some what different.

Researcher: Because you chose them or?

Jager: Just because of the supplies in the school. But still I think it would have been of great benefit to have had samples of everything ahead of time. So we could all be familiar with what we were using. We can get in there and get to the experiment and what we are supposed to do and then we can, maybe, have some more time to explore a little bit more. And maybe even refine our procedure a little bit more so we can control more of the variables and get a little bit better readings ---

Researcher: But the fact that you could report where ever you were did that reduce the pressure a little bit; that you know that it is a work in progress?

Jager: Yes! Definitely! You go in there especially with the pop can lab. We didn't have the pressure of --- You go in there and you have to have good results or else you are going to --- It's not like a scientific experiment where we you are getting paid and you are supposed to have good results. It is a learning experience. I think for a student, you go in there and you want to get good results just so, that when you do your analysis and everything turns out alright and you get low percentage error. It is kind of gratifying (smiling) as a student knowing that you are learning and you can still produce something that is worth while and beneficial.

Our conversation at this point seemed to focus particularly on process of investigating relating it the student's learning experience.

Jager: The open-entry activities to me seem I guess more like an open world. You are not sure what you are going to get. It's time to do more discovery where as the ones that you have a definite problem to solve you are going with a definite procedure. You are just kind of doing it by clockwork and practicing the skill that you already have, where as with these you have some choice of your own. You get a chance to make your own procedure. I think it is more of a learning experience. If you go in there with your own procedure that you have made as a student it almost reflects your abilities in a way."

Researcher: So of the two which do you think you learn chemistry better from?

Jager: uhmm! (Stops for quite a while and put both arms on the bench and looks ahead of him as if in deep thought). That's a good question!

Researcher: Or is there one?

Jager: I am not sure there is one. I think you have to have a little bit of both because if you go in with open-entry all the time, there is the possibility that you are not going to, in enough circumstances, get the results and to use the procedures that you might need to use. Whereas if you go in with kind of a set lab where you are using procedures that are known and tested, and something that is intended to be learned by you, I think it would be more beneficial in that case. So I think you do have to have a mix

It seemed to me that students' understanding is sophisticated. They know that to make sense of school chemistry investigation is not an either/or situation. Their experiences inform them that they need the different experiences—the traditional as well as the nontraditional open-entry labs. From Jager's answer, for instance, he realized from his experience that meaning making was complex and required processes that exposed students to multiple ways of doing chemistry. I therefore moved on to inquire about his experience of uncertainty. "What about certainty? Can you comment on the issue of certainty with these activities?"

> Jager: Well, certainty in the procedures like I said earlier, when you go into the lab with a preset procedure you feel some certainty in it while you are doing it, but then in retrospect you can do your analysis and find that it didn't turn out as well as you had expected. You might reconsider the procedure and think; well may be it wasn't as certain as I thought it was. I think even with that though, it is almost easier to identify where you went wrong because in your own procedure you might have a greater number of places where you would be uncertain because you have designed it yourself.[15] So you have more of an overall insight into it. Where as step-by-step you can say, well in this step that procedure that I used is something that I am not really comfortable with, like titration or whatever. So you might think well I think this was above my skill level and you put that in your evaluation say, well I probably wasn't as comfortable with the titration as I could have been. Personally, when I make something myself, I have my own creation I am a lot more critical of it in more places. Or just overall I think I completely took a wrong approach with this whole procedure. It didn't turn out right.
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> Researcher: So you tend to analyse your own creation much more, and more critically.
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> Jager: Yeah, definitely and in a broader scope I think.
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> Researcher: And you can revise more steps than with a preset procedure.
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> Jager: Yeah, That's right. Whereas if it is something that you go in there with a background thinking that it has got to be a pretty good procedure overall, it is not necessarily the procedure that was flawed but just may be a part of or that was not performed properly because of skill or whatever.

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[15] Jager's comment alludes to the complexity inherent in open-entry investigations. He recognized that with this complexity there is uncertainty at various levels of the investigation. Designing the problem-solving strategy gives you more insight into what possible problem areas one could investigate.

Traditional laboratory activities, often found in textbooks and laboratory manuals, have procedures that have been tried and tested by others. They are often presented as sure flawless ways of doing certain processes which results in students not questioning them but rather accepting them as they are. Jager's analysis alludes to this epistemological understanding on the process of doing school chemistry laboratory activities. Students are therefore left with the option of the less certain variable, their skills, to critique if there is an unexpected outcome.

Intuiting a Re-membering of the Almost Forgotten

Fensham once asked, "What happened to intuition in science?" In that paper he suggested that the possible explanation for students' inability to develop personal meaning could be because they are not required to use their intuition in learning science. In doing these open-entry investigations, perhaps, students could have to use their intuitive knowing and thus bring back that bodily knowing back into the repertoire of the meaning making processes in high school chemistry. In my conversations with Ursula she had voluntarily brought up the Group 4 project in her opening remarks and spoke a little bit at length about it, I sensed that it must have had some significance for her. I was intrigued to find out what she thought about the entire process of doing that activity.

> Ursula: *I thought that one was interesting since we were the first year to do the Group 4 project. The way we did it sort of, testing the instruments, instead of really testing a prediction, like using the prediction or being right and then evaluating, instruments based on how accurate and how reliable the results were, that was different from what we would normally do in class so I enjoyed the Group 4 project a lot.*

Ursula, with excitement in her voice, mentioned that the Group 4 project was different from what they normally did in class and that made it enjoyable. Pedagogically this was informative as it pointed to the kinds of contexts some high school students could find interesting. Our emotions are complicit in the meanings we make. I am happy that I had asked Ursula for an interview. In a way this was a re-membering act in which I remembered the student I almost forgot. My act of interviewing her enabled me to focus on her, to recognise and acknowledge her contribution towards this study. Ursula was re-membered as in bringing her in to the membership of the community of knowers who contributed to the evolution of this study. I know I will always remember the impression she left me with. I wondered what she would think about the other three open-entry activities. I also wondered about the pedagogic, epistemological and perhaps the ontological implications this research had for her. I could only deduce that in ways she positioned herself in a manner of speaking as she talked to me about the different issues.

Open-entry activities tend to be similar to everyday problem solving in that the investigative strategies used can draw from students' embodied and intuitively expressed knowing arising from their experiences with everyday phenomena. In Irene's lived experience of these open-entry investigations was it possible that she could recognize times where she, perhaps, drew upon her knowing that she could possibly identify as not originating in the science classroom? "Do you find that it draws from anything that you have learned from home?" (Irene quietly paused with a quizzical look) I mean anything that you did not necessarily learn from the chemistry class or chemistry lab?

> Irene: Oh yeah, (beaming with a smile, remembering something) When I was young I used to play with these little light bulbs and batteries and wires. So when I tried to electroplate the disk, and I poured some electrolyte or copper sulphate on the disk and I know that it wouldn't work but I *just wanted* it to work. Of course it doesn't work that way. Just looking at the disk I knew it wouldn't fit in the beaker or Erlenmeyer flask. So I just thought there must be a better way of doing this but since I don't see

anything else around, I m just going to try it this way even though I know it wouldn't work.

Researcher: Right!

Irene: Even though that was not rational, I just didn't want to give up.

Researcher: You had to try it out!

Irene: Right! You look at it, it is obvious [the circuit is not complete] but still you want it to work (laughing about it).

Researcher: What about the fact that you had to use acetone for the pop-can. Is it something that you would have thought about prior to --- I mean had Dr. Meulenberg not mentioned it would you have you thought about it as possibility?

Irene: I thought about using the acid to remove the plastic coating and then I thought the solution inside is normally acidic in the first place and so I wondered how I could remove the plastic but I hadn't thought of acetone.

Irene had clear examples of incidences of interactions in the open-entry investigations where she did not draw only from her school knowledge but also from her everyday lived experiences. She knew that some of her ideas were not scientifically rational and yet she would not give up on the idea before trying it out. Perhaps in this chemistry learning setting the viability of our ideas and actions is tested and it develops embodied meaning through action. From the enactivist notions of embodiment we could, perhaps, make sense of the tendencies to want to try out these non-rational ideas. In doing and in testing the ideas the body comes to know the viability of these ideas in more than just one way, the rational way but also tacitly, through bodily cognitive networks that are part of the meaning making processes.

Researcher: So did you think about the top of the lid as well?

Irene: (raising the tone of her voice to express her surprise) I didn't think about the lid. I thought of the solution in the can and not of the top of the can.

Researcher: Right.

Irene: (smiling and slowly dragging her words) I keep wondering about my mental capacity or whatever ---

Researcher: no, no, no, no.

Irene: Well I do. I do because it seems like there are things that are incredibly obvious when presented to me, that I don't see and may be I should see especially since I am seventeen or eighteen.

Researcher: But you can't see everything. There has to be something there --- I mean even for Dr. M., I think there are times when somebody has to point out something to him.

Irene: Yeah!

Researcher: Because naturally there are times you may overlook something and when it is pointed out you say Oh! I should have thought about it. So it is not that there is something wrong with your brain or mind it is just the way that we deal with things unless our focus is brought to it, we don't see it. Because sometimes you may be looking in a certain direction but you don't see certain details until your focus is drawn to them, then you start seeing those details.(Irene nods in agreement and exclaims, "Mmmh!")

Meanings that emerge for us are embodied. Since they emerge out of our being in the world, they are about our being in the world. Theoretical meanings also have a bodily connection since they their sense tends to come to us in languaging through models and analogies that are grounded in our bodily experiences. We are therefore closely linked to them. In a way they say something about us and about our relation to our environment. They may enhance our perceived self image or they may lower it. They may also trigger within us emotions and other bodily interactions that may lead us to wonder and question ourselves or our capabilities. This is part of the way we make meaning, with and through our minded-bodies/embodied minds (Varela, Thompson & Rosch, 1996; Lakoff & Johnson, 1999). Irene's wondering about how her brain works or her mental capacity is all part of the complex processes of meaning making which she has to make coherent. A reassuring word, an example of other people's living in the same condition may perhaps be pedagogic and ethical, helping to restore or boost the self-confidence that could be at the brink of collapse. This pedagogic act may be a way of existing beside and legitimising "an other," an act that Maturana and Varela (1987) may recognize as an act of love that create spaces for others to co-exist with us.

Going Back and Trying Different Things

> Ursula: *The iodine clock reaction? That was on there [the videotape] -- it didn't show me doing much. We did that one in chemistry 20 as well. When we did it this year it was sort of, we used similar procedures and everything but I think I had more background knowledge. So I understood more why the different variables affected it and also it was more this year, sort of learning about how to solve technological problems, technological problem-solving [in which we were] going back and trying different things. It was a work in progress just like the other one, with the pop can we were sort of trying to see what works, what gets you the right answer. A lot of creativity was involved in manipulating different variables, but you also have to be very careful in your procedure because you can only change one variable at a time so you get good results.*

Ursula brought up several interesting ideas that I felt were important to the meanings one made of the open-entry investigations. She noticed that in these open-entry activities their actions were not linear. They were "going back and trying different things. It was a work in progress" Researcher: How do you feel about activities where you go in to the lab thinking, this is what I am going to do and then you find that as time goes on you might have to change your problem statement or even change the original problem that you had and do another problem that emerged from the activity that you started out with?

> Jager: I think in the beginning of this year I was a lot more uncomfortable with that. But as the year went on, we did some of these open-entry activities, you begin to realise that that is kind of natural outcome of a lot experiments. That you get in there and you do it and your results don't quite prove anything to what you are testing. So then you go back and think did that actually show me anything of benefit?[16]
> Researcher: Yes, that is a useful question.
> Jager: So then your work wasn't a complete waste of time, it wasn't useless. It might tell you something else. At the beginning of the year, after having

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[16] Students seemed to draw from their everyday problem-solving approaches from which they intuitively knew that problem solving is not a one-shot linear process. They knew that in these settings every intermediary step taken, if it does not give you a direct answer to your problem, brings you closer to it. It just depends on how you look at it. They were therefore able to deal with the twists and turns of this somewhat naturalistic problem solving presented by the open-entry activities.

done mainly labs where you went in the lab and answered the question provided, especially in Chemistry 20, and everything usually worked out pretty well, it was a new experience. This year we went in there with a few different kinds of things, especially with the Group 4 project. We went in there pretty much broad scope with barely a definite problem or procedure.

Researcher: Yeah, and even Dr. M. did not have the answer.

Jager: Yeah, there was no authority to base any prediction on. We kind of went in there with a very open-ended problem; equipment we did not know was going to work at all even, and a wide variety of equipment. So I think with that it was quite interesting to have a situation where you know there is not going to be definitely a right answer even the instructor is kind of wondering along and working along with you. I think as the year went on, towards the end, I got a lot more comfortable with realizing that your results are not always going to show you something that leads to answering your problem directly, turning that around and making it work for you.

Jager's initial discomfort arising from uncertainty inherent in open-entry activities gradually changed as he experienced numerous situations that were uncertain or not well defined. He was able to turn what initially appeared as a road block into a possibility and made "it work for" him and building his confidence in his ability to do so.

Researcher: What about activities where you found that you had to falsify predictions?

Jager: That was definitely something new too. That was at first pretty uncomfortable because you think when your results falsify at first you think there's something you did wrong and it can't be right for whatever reason.

Researcher: But when you find that your results are right, how does that feel?

Jager: I suppose it feels good but I suppose it is also very hard to accept too because you go in there and make a prediction and usually you are seeing how close your experimental results come to your prediction whereas in the case where you find they are completely off but yet you are still right it is a very interesting experience. In a way it is even more of a learning opportunity there when you find that you are actually coming out with a strange answer and having it is right. That is definitely a good feeling.

Researcher: Does it give you a boost and make you think that I can make a difference in chemistry too?

Jager: It does. It definitely does and it makes you more sceptical of the rest of your results from that point on. You go in there and you are not sure, you go in there doubting, you are never going to say "these results have got to be wrong!" You go back and then in the steps where you are evaluating your procedure, I think you'd be much more critical of that later and do it in a much more useful way. Where you are not necessarily saying that your skills were wrong and if you go in there and find that in some areas they may be not as good as they could have been but then you have to also consider that well, could the differences in the skills have caused a problem in the results this big?

Researcher: Right. So you get into a deeper and different level of analysis and evaluation not just surface.

Jager: That is right and with this analysis you can then say, if the problem skills and the technologies and the materials we used couldn't have produced an error this great and this drastic in all our predictions, then you go back and say well we have to test the prediction and the authority for it.

Researcher: I think what you are telling me is that it has opened your eyes to the fact that you can make contributions to the chemistry world am I right?

Jager: That's right. And it is not that we weren't exposed to that either. It's just that I guess as a student you don't really expect it until it happens.

A shift in Jager's epistemological understanding of the processes of meaning making has emerged from doing the more open-ended falsification activities. They offer students possibilities of not questioning the skills only but also the procedures, the predictions and the authority that originated it. By doing these activities, students are not just exposed to it. They develop an embodied knowing—a knowing-how-to.

Students' experiences of nonlinearity in their laboratory investigations required a shift of paradigm—a changing of mind sets or predispositions and a creating of new habits of mind. Different students went through this shift at different paces. This is reflected in the different interpretations students had. This shift of focus seems to be a necessary part of the process of successfully engaging in and making meaning in open-entry investigations. Irene seemed to be in transition. Her language suggests that she has mentally seen the logic behind the change and even bodily she has struggled with making the switch but perhaps out of other factors tends to want to have a clearly outlined procedure before she embarks on the physical manipulations.

Researcher: So do you find that when you are engaging in an activity often times you have to change your orientation or do you find that new problems arise that you have to think about, that probably before the activity you didn't think?

Irene: Yeah! That is why I think the kind of labs that we have done this year where we actually have to create a problem and create the design, I think should be more in the curriculum.

Researcher: You think there should be more.

Irene: Yeah (nodding several times and emphatically says) absolutely!

Researcher: Why?

Irene: Well, verification of what is already known is --- it validates. It does what it is supposed to do and enforces it in your mind but it doesn't create the kind of environment where your mind has to extend beyond what is just given to you in a text book. And you say oh well this is what I know. This is what I am going to get in the exam. But the other kind make you think and they make you conscious of all the variables that have to be controlled. (Researcher exclaimed, Mmh!) And what is actually involved in the scientific process.

I was intrigued by this exchange. What an exciting paradox. Here was a student who clearly seemed to appreciate the challenges and pedagogical value of open-entry activities in opening up possibilities for more personal and embodied ways of knowing, who also appreciated the limitations of a singular approach to doing chemistry but in her own doing seemed to be trapped in approaching these open-entry investigations mostly from the traditional approach.

Ursula's reference to being very careful in one's procedure could perhaps have been learned by repeated stipulation in traditional laboratories she had done previously but the tone with which she emphasized "very careful" suggested that she had developed an embodied sense of what it was to be very careful which could have come consequentially with being immersed in the interaction. Students had struggled with controlling variables and determining what variables significantly affected their investigations. It appeared to me that she too might have struggled with it, gone back and tried different things and ultimately found ways of overcoming that challenge resulting in a tacitly and yet embodied understanding of what controlling variables meant. I therefore wanted to find out what she had learnt, in general, about controlling variables from doing the activity.

Both Jager and Ursula seemed to have developed for themselves explanations about the non-linearity of the process of engaging open-entry investigation that allowed them to handle the going back and trying different things. "That's an open world" Jager calls it; meaning that 'that is the way life is'. This could come from someone who has lived different and yet related experiences that allowed him to see doing open-entry investigation as similar to problem solving in the process of living. Irene on the other hand seems to be lingering at the edge where she has psychologically realized and appreciate the openness and the nonlinearity but is struggling to work with it and embody it. Her history of interactions in laboratory investigations may perhaps explain this.

Immersing in the Interaction

> Ursula: (smiling) *I think generally it is easy to say and write up a procedure "control it" but when you are actually doing it you have to pay attention. You have to be very careful and very alert to make sure you are actually controlling everything that you say should be controlled. In terms of temperature, if you need to get a warm solution or some thing or to make more of a solution it could be a totally different temperature. Even though you have specified in your procedure that everything will be constant concentration, constant temperature, you don't actually know until you go into the lab whether that will be true. You have to actually test to make sure that you stay true to what you said.*

An important observation had been made that in my view was critical to making the iodine clock investigation meaningful. Ursula learned that, "You don't actually know until you go into the lab to actually test." In the history of the finding of the structure of the DNA, Watson and Crick were immersed in the process of finding this structure. "Even during good films I found it almost impossible to forget the bases." (Watson, 1968, p. 181) Watson and Crick spent hours in the laboratory and "[g]enerally, it was late in the evening after I got back to my rooms that I tried to puzzle out the mystery of the bases." (p.182). It appears that in those last few days leading up to their discovery Watson and Crick engulfed themselves in feeling out and feeling for the DNA.

> Not until the middle of the next week, however, did a nontrivial idea emerge. It came while I was drawing the fused rings of adenine on paper. Suddenly I realized the potentially profound implications of a DNA structure in which the adenine residue formed hydrogen bonds similar to those found in crystals of pure adenine" (Watson, 1968, p. 184)

In a similar manner, Ursula had learned in the doing that controlling variables demanded more of her attention and skill. This student had learned in an embodied sense that to make meaning of the open-entry activities, she had to be immersed and actively participating in the investigation and not just following steps. "When you are actually doing it you have to pay attention. Be very careful and very alert to make sure you are actually controlling" I can almost hear her slow deliberate pronunciation, stressing every word with a slight back and forth movement of her head, looking me straight in the eyes, as if to add bodily emphasis to what she was saying. Only a knowing body could express such deliberate and intense emphasis on the action. It seemed to imply to me that she wanted to express the need for total immersion in the doing which involved constant reflection-in/on-interaction, I was keen to know what she had learned from the other open-entry activities, so I enquired about the pop can cell.

> Ursula: *In terms of that one I remember after reading our labs. I think Dr. Meulenberg mentioned that we weren't as creative in the problems that we used as he would have liked us to be. I wasn't too sure exactly what he meant by that because that's a lab taken out of a text book. It has, it suggest what kind of problems we should be solving. So could you give me insight into that?*

I was interested to know how Irene lived the paradox of wanting to have a pre-outlined procedure and having to work with not having it. "Do you mean you couldn't get a sense of all the variables prior to doing the activities?" I asked Irene.

> Irene: I do get a sense of that but not as when I am actually in the lab doing it myself.
> Researcher: So new variables emerge as you are doing an activity?
> Irene: Yes!
> Researcher: So how do you deal with these new emerging variables?
> Irene: Well, you try to either control them or you can see how you solve one of them as problem, how you can control a certain aspect of your experiment. (Researcher urging Irene to go on, nods) Sometimes it takes group work. Sometimes I prefer if it wasn't in a group.
> Researcher: The comments you are making are very interesting. Do you find that you are drawn more into thinking about what you are doing, in a chemistry sense, when you are doing activities where the procedure is not set out for you, where you have to think of the procedure yourself?
> Irene: Yes, yes. (Nodding vigorously) Yeah!
> Researcher: Does that draw you into thinking more?
> Irene: Yes, yes. And I find that more useful in the application of what I have learned over the past two or two and half years. (Researcher nods) And applying it in a lab I find that very useful. It is not just a review of what you learned from this semester or this week. It is what you have learned about science, and what you learned from chemistry -- over at least the two years.

Irene here reiterated her earlier claims of using or applying science knowledge learned from class to laboratory work. Although this approach is successful in traditional verification laboratory activities, it may limit the kinds of interactions students engage in and the meanings students make. Perhaps the kinds of meanings she made reflected this. I decided to explore this later with the student.

> Researcher: If I was to state that hands-on activities give you a different insight into chemistry, what would be your reaction to that?
> Jager: I definitely think that is a valid statement. When you learn it in the classroom I think that it kind of solidifies it when you do it hands-on. You learn a concept and then you almost want to go and test it too so you can determine for yourself whether it's actually applicable to the real world and really do chemistry experiments to answer your problem.

Students recognized that immersing themselves themselves in the doing of chemistry allowed them to determine for themselves and thus develop personal meanings about phenomena.

Seeing Possibilities

Ursula could have just answered the question I asked her, but her mind was keen on making meaning for herself. Although the course class-work was completed, she still remembered a comment the teacher made during the post-lab discussion about the pop-can cell activity that she was not clear about. The teacher's comment was not referring to this group specifically but to the class as a collective. There was less variety in their problem solving approaches. Ursula also displayed a conscious listen to the teacher that enabled her to pick up cues from what the teacher said and use these cues to direct her interactions. This was a chance to talk about it. So I offered her a brief interpretation of what I thought the teacher was referring to and she seemed satisfied with it. "Well, there are so many other things that could have been done. Some people in the past what they did was test all the electrodes that were there and all the solutions that were there, found different combinations. And even as they were carrying out the activity if a problem came up, they tried to solve that problem. So I guess a lot of people in your class were doing the same thing."

> Ursula: (Nods) *Right! What Mike and I did we started off with hydrochloric acid and used all the different electrodes with that. Right from the beginning, there was a clip on the video showing us getting tape around the edge f the pop can. That could have been a problem that we encountered but he [Dr. Meulenberg] said before in class to make sure that we don't have the electrodes and the pop can touching. So I guess we had to figure out how to make sure that they didn't touch. But if he hadn't given us that information, maybe we would have had the electrodes touching the pop can and the copper or whatever it was. And then we would have had to think why isn't this working or why is our battery "shorting"*

> *out here -- it is because the two are touching. So we taped that up -- it was okay, it worked. We didn't really run into a lot of problems. We tried carbon, copper, and zinc all with HCL and then we changed electrolytes. We used sodium hydroxide. I think, was that the second one. And then we used the three electrodes again with that. So we got quite a variety of results with that. So we did a couple trials with each different one just testing the voltage each time. (Pause) What else? Also Dr. Meulenberg said something before we went in about people from the other class having problems with their aluminium can, having it working at first and they would think it was sort of deteriorating and they thought it was giving them smaller voltage. So I think that would be something interesting to look at, to find out if there was something that changed with the pop can over time. And if there was try to (at a theoretical level) find out why that was. Also the problem with the pop can that we had when we had to remove the coating with the acetone, probably you could think that we were told that because I think if we were in the lab trying to figure that out. We probably it wouldn't have come to mind. So it would have been stuck right there and we wouldn't have been able to really make much progress. We could have tried a few things but probably we wouldn't think why don't we rinse the pop can with acetone, just in case.*

It would appear in retrospect that Ursula was thinking of possibilities --of ways interactions could go-- which may imply that she was ready to see or her mind was prepared for different possible outcomes that they could act on. In addition, Ursula's readiness for possibilities implied by her mentioning some interesting things to "look at, to find out if there was something that changed with the pop can over time," points to her epistemological understanding of the process of meaning making in chemistry. She is a knower who knows that she is the creator of her knowing and her world. Ursula consistently raised comments the teacher made in class which points to her listening skills[17]. Her meaning making was significantly influenced also by working beside a more experienced other. In terms of what she did, she listened carefully to what the teacher said and found ways to improve her investigation. In a Maturanian sense, she was structurally coupled to her environment, choosing from her environment energy rich matter that could help her make meaning for herself in both the doing and the thinking about the investigation. Having described particular learning moments about specific investigations, I was keen to know what Ursula's overall impression was with open-entry activities. What did she think about the process of doing this kind of activities? What lessons would she take away with her after doing the activities?

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[17] This may indicate how she values the teacher's contributions in this setting and in her learning chemistry as we usually pay more attention to what we value

> Ursula: *I think it has taught me a lot about science and how chemists think of science especially compared to the way we also do labs and do problems and evaluations in biology. They are very different perspectives. The way Dr. Meulenberg emphasises Karl Popper. I think when we do the labs and you get your evidence especially if it's something if it's a falsification, it goes against an authority that you should be getting the results but you are not getting there. Then I think that teaches you a lot about science and how progress is made and how new theories get formed. In general I don't think that sciences are really my strongest subjects in school. I am not sure I would pursue it in university also having not taken physics. I don't think I would be able to go into a lot of programs. It is always a possibility. I enjoy doing labs and learning about it. But for me it's not something I could imagine myself doing the rest of my life. Like I was telling you, it's hard for me sometimes when doing a lab to think of different ways of approaching it. Like I was asking you what Dr. Meulenberg meant when he said we should be trying different things but if someone explains to me I would understand and say, Oh yeah, that would have been a good idea but my brain doesn't really work in that way.*

These open-entry investigations seemed to have triggered some self-reflection in a number of students. Because the activities were students' own creation in terms of the design, the problem posing, the problem-solving and the communicating, students felt a greater degree of ownership of the investigations. They felt personally tied or linked to their creations to the extent that sometimes students felt the investigations were a test of how they think or a test of their intelligence. In Ursula's view doing science seemed to require a different kind of brain-work than she thought she was capable of. Whether this was an accurate self-assessment or not, that was what she felt at the time despite her success with all the investigations. Her comment about physics made me wonder whether she linked her perceived inability to learn science fast or to come up with interesting ideas on-the-spot, to not having done physics. So I asked whether she thought that her not doing physics had an impact on how she learned and understood chemistry.

> Ursula: *Well, it's hard to say because I have very little background in physics so I wouldn't know if anything really related to physics. But I took physics 10 in grade 9. I don't think so because even I am taking biology and I don't think even if I wasn't taking that I don't think it would have impacted the way I understand chemistry. Oh by that logic then physics wouldn't have either. A lot of it, it seems they are very independent at least in high school level, maybe later on they become more interrelated.*

Ursula had already demonstrated a readiness or a predisposition to analyze her own processes. This triggered different thought processes in my mind. I could not resist finding out what further investigative problems she thought could emerge from these open-entry activities. "If you had a chance and time what kinds of follow ups would you do from the activities that we did?"

> Ursula: *For the iodine clock reaction, I can't remember which variables we tested but I don't think we had time to do all of them, but maybe manipulating just temperature. It would also have been good to look at concentration to see maybe be if one variable was easier to manipulate than others or it can give more consistent results and then determine why those skills are easier something like that. In terms of the Group 4 project maybe after we had completed the evaluation of the instruments it would have been interesting to use the instruments that we decided are most accurate or most reliable to test different authorities say from Aqualta. Or test even using the instruments to test different bodies of water at different times of the year or anything like that and see what kinds of results you get. It would be a very different experiment because you would be testing a prediction, you wouldn't be testing the equipment again, but we would still be using the results from when we began.*

Having talked about theory verification and also knowing some of the justification behind the early discovery learning theories regarding hands-on in science, I was inclined to find out what this student thought about students' theory building and hands-on activities. Did students recognize that there exists circularity in chemistry between doing and theory where the doing can give rise to theory and also the theory can give rise to theory? Was that part of global meanings students had, although not necessarily from the open-entry activities?

> Researcher: So in consolidation of what you did in class, hands-on activities are useful. What about in building theories, do you think hands-on activities can help develop an insight into theory building?
>
> Jager: I definitely do. I am not sure though that at the high school level or even a bit beyond that that it might come easy for a student. Like in physics for example my teacher last year gave us a whole bunch of examples of how through various experiments they were able to build this theory. It all makes sense but then we you go and try to think yourself. Now could I have designed these experiments in such a way, based on evidence from the first experiment, how you could change that into a second experiment that might help you get closer to the answer.
>
> Researcher: Mmh!
>
> Jager: I think that it is definitely a fairly involved procedure to do that. I am not even sure in some of the cases where I looked at that and I thought now could I do that? And I thought no, I am not sure! I think it's a case of giving it a try, I guess. I don't think we do give it a try at this level at least. But it would be worth a try I think. It would be interesting to see if you can do more synthesis. With the labs we did this year we didn't do a lot of synthesis; we did a lot of evaluation but not a lot of synthesis where you are going in building another experiment to either further explore your claims or your conclusions about your results in a different way as well as even completely designing a whole new problem and experiment to go beyond.
>
> Researcher: Mmh!
>
> Jager: I am not sure exactly how that would work and at what level but I think it would definitely peak a lot of students' interests to do that. It would make it a lot more of a worthy experiment to do it and to go a bit beyond that even further for a student.
>
> Researcher: Well I guess because of so much content that you have to cover there is very little that you can do. But falsification experiments, in a way are an introduction to that because then you start thinking differently about what you originally thought.
>
> Jager: Sure, that is right.
>
> Researcher: You start developing an intuitive sense of what could possibly be happening and you can then expand it a bit.
>
> Jager: I think with the falsification experiments the least that could be done I think is do the design and the problem for a follow up experiment. How you could re-test this to see really whether it was false or whether it can be verified in another way.

Researcher: Yeah, that is interesting.
Jager: Not necessarily to do another experiment but just to think about it and design and prepare and then evaluate it based on the student ideas on how you could re-work it.

From the interviews with students various significant and interesting pedagogic meanings emerged. It was interesting that both Ursula and Jager mentioned physics in their reflections. Physics provided Jager with a point of reference about theory building. For Ursula, she was not too confident about doing science at post secondary level because she had not done physics at high school. However, she could use biology as a reference and compare her interaction in chemistry with those in biology. So in some ways they brought their various experiences of science to the broad questions I asked them.

Students' understanding of chemistry laboratory activities at lower grades had been limited to closed type of activities where they verified theory. The activities were closed to students' everyday ways of thinking about phenomena. They were closed to students' creative input. They were closed to use of their intuitive problem solving skills where they could pose problems, design and carry out their own strategies for solving the problems. As part of the Chemistry 30 laboratory program the teacher had introduced the students to laboratory activities in which they tested and falsified theory. These were not part of the research. This was an eye-opener for many of the students interviewed. All three interviews presented in this chapter, students talked about it as a new experience. The falsification activities were openended in the sense that students could come up with different solutions to a problem that was posed for them. Jager, for instance, spoke of the excitement one felt. "In a way it is even more of a learning opportunity there when you find that you are actually coming out with a strange answer and having it be right. That is definitely a good feeling."

It would seem that activities where students falsified predictions or theory provided a transition for students to be able to handle the complexity and uncertainty presented by the open entry investigations. The falsification laboratory activities seemed to offer various evolutionary pathways for students where it was no longer a serious shock or impediment not to know or to be uncertain of the outcome and to have results and answers that were different from other students in the class. Open-entry investigations extended the notion of uncertainty by not providing a problem statement for the class, by not providing a design or a procedure for solving the problem. These investigations increased the level of uncertainty and complexity of students' doing chemistry. The following schematic shows a simplified representation of this co-emergent evolutionary process in students' meaning making.

Re-Viewing Complexity and Uncertainty in the Laboratory Investigations

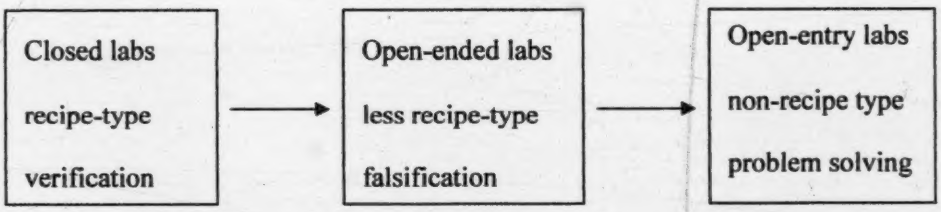
Closed labs
recipe-type
verification
Open-ended labs
less recipe-type
falsification
Open-entry labs
non-recipe type
problem solving

Figure 15. Evolutionary transformation of laboratory investigations.

> It would be better I think if we start off with activities with a procedure and then move to those without the procedure. You would have already tested some. You've already experienced something you have some knowledge, so you are able to decide for yourself and you'd be more creative and be more intuitive. You can compare your results with those of other students by following a procedure. So I think it is better to start off with a procedure so we get ourselves into labs and knowing what to do and then do procedures so we have to think about it (Salome's conversation with the researcher)

Students recognised in their interviews that there was a need for all these types of activities for them to develop a broader understanding of chemistry. Their over all meaning making of problem solving processes in open-entry activities drew from experiences in all three. It was not a matter of choosing one or the other. Irene suggested that there should be more of the open-entry type, perhaps, because of what she felt was a deficiency with a program that traditionally emphasized closed activities.

When students eventually conducted the open-entry activities, although they were uncertain and hesitant in their actions, they were able to handle that uncertainty and complexity. The uncertainty inherent with the open-entry activities was essential because it enabled students

- to enact their own understanding of knowing, to test it and to evaluate it
- it created opportunities for students to build confidence in their logic and in themselves.

Ursula, answering my question on whether they learned more from open-entry activities or from traditional verification type, mentioned that "I think the ones that are sort of open at the beginning and you are unsure of yourself, [you learn] more because you learn a lot from your mistakes. You learn a lot from asking." The uncertainty initially unsettles students but if gradual success is experienced as investigations evolve, students' self-confidence and confidence in their skills and capabilities increases. Students, perhaps, need to go through this uncertainty cycle enough times in their science learning to be able to model the nature of science. Irene, Jager, Ursula and other students interviewed recognized and acknowledged that uncertainty forces you to extend your thinking; a knowing that reflects the student's sophisticated knowing that there is more to knowing science than what may be presented in class.

The use of unfamiliar equipment initially seemed to present problems for students, for students who were not overwhelmed by it, it eventually turned out to offer possibilities. Once students recognized that they had to work with the equipment, they seemed to draw from other experiences they had had. For instance, the Group 4 project experience where students tested equipment, checking if the instruments worked, checking the consistency by repeating measurements and accuracy by comparing with other known measurements, offered perhaps, a different way of engaging the unfamiliar equipment. They gradually developed ways of testing, and using the instruments.

Students repeatedly mentioned that open-entry investigations are beneficial for personally meaningful learning of chemistry and should be included in the school curriculum. For open-entry investigations to be successful in a school chemistry laboratory program the following support structures must exist. Laboratory activities must allow

b) replication, iteration, cycling back

b) choice of equipment

b) choice of experimental design

b) choice of procedure

b) choice of skills

b) evaluation of all the above

Students' Perceptions of Open-Entry Investigation for Their Future Learning

Through out this research students had demonstrated sophisticated ways of knowing. Many students were creative and could think on the fly so to speak. I suspected that these open-entry activities had had some impact on their learning and I was curious to find out if the students had any indication of this from what they had learned about themselves.

> Researcher: Did the activities in general, impact the way you learned chemistry?
>
> Irene: (repeats) did the activities impact the way I learn chemistry - Uhm (then stops to think).
>
> Researcher: Or do you think your learning has changed as you did the activities - I don't know I am just ---
>
> Irene: I think so. I think when I am reading a textbook I question things more [now] and in doing so I am able to remember the content in a chapter or whatever a lot faster than I used to.
>
> Researcher: Mmh (nods)!
>
> Irene: It has to do basically with looking at a statement and then forming in my mind questions about it for example. So what is the first reaction or what is the reverse reaction of this or something? So that just creates a better understanding, I guess.

I needed to find out from more students whether they thought doing these activities had had any impact on their learning. I also asked Jager the question I raised to Irene.

> Researcher: How did you see, talking in general terms, the set of activities that we did, the open-entry activities towards your learning. What do you think of them?
>
> Jager: Yeah. I definitely think they are a lot more --- Those open-entry ones to me they seem I guess more like an open world. You are not sure what you are going to get. Its time to do more discovery where as the ones that you have a definite problem to solve and you are going with a definite procedure. You are just kind of doing it by clockwork and practising the skills that

> you already have or you have acquired. With this [the open-entry] you have some choice of your own. You get a chance to make your own procedure and then when you are looking back on it, I think it is even more of a learning experience. Because then it's a procedure you'vet created that you can critique and see where you could have made improvements. Then next time you get to do that you might or it might click on to you have actually performed one of your own procedures and that it might have some problems. Where as if you are looking at somebody else's procedure I think its harder to critique because you are not sure who has made it and what kind of background they have and whether it was intended for people with skills and better equipment. Where as, if you go in there with your own procedure that you have made as a student, it almost reflects your abilities I guess in a way. You go in there and you don't make a procedure that is really difficult, that is going to expect a lot of skills out of you. It is going to be something that is going to be fairly simple and to your abilities, and something that would hopefully get your problem answered or figured out.
>
> Researcher: Of the two types that you mentioned, which one do you find that you reflect more?
>
> Jager: Definitely the open-entry. You reflect more because, like, you don't just have your analysis to reflect on and whether you have results but you also have basically your own creation to reflect on, your procedure and all that came with it; all the pre-preparation to the lab that you had to put work into.
>
> Researcher: So you even bring your own intuition to it and test it?
>
> Jager: Yeah, exactly!

Jager's observations seemed to corroborate what Irene had said. I wondered what Ursula would say and how she would respond. The interview with Ursula had taught me that for this student a complex and dynamic knowing of high school chemistry and science in general had emerged. If this was true, it would have implication for the student's understanding of herself and her learning. I knew her knowing was sophisticated and complex and that she could handle questions that were self-reflexive. I asked her about her learning. "How do you think doing this kind of activities impacts your learning process or learning style?"

> Ursula: *Well, like I said before about Karl Popper and falsifications without doing labs, without actually falsifying authorities it wouldn't be as clear in my mind that what we are learning is not necessarily true. What we are learning*

> *could be true but there could be more to it. By doing these experiments and testing theories it's the best way to learn and get new theories, new knowledge.*

Ursula seemed to have developed patterns of understanding of the process of doing chemistry research that would perhaps not have come without doing these open-entry activities. Doing chemistry in these settings was much more than just action in the laboratory. It was not, to use Jager's words, clock work. It was more unpredictable, more social, more personal and more challenging. It expanded students' field of activity by allowing them to be owners and creators of their own investigations which traditionally had not been the case. She had been immersed in the process enough to start seeing an evolution in processes from closed traditional laboratory activities, to open-ended falsification activities to open-entry investigations that called for their creativity. I wanted her to confirm what I thought I heard her say. "So in other words what you are saying is that when you actually do something you learn more from it."

> Ursula: *Yeah, I think so, definitely. And also when you asked me before about controls, when you actually do it you realize a lot more how important controls are. Because, especially with the iodine clock reaction, if you weren't very precisely controlling concentration or whatever variables you were manipulating it was very difficult to get consistent results and it really shows you the importance of that.*

When I showed the teacher the transcript of the interview, and we talked about it, teacher could remember with excitement how Ursula had come to him to enquire about Karl Popper and falsification. With gleaming eyes she came and asked me "do you mean we really can falsify authorities?" I knew a light bulb had been turned on, the teacher told me. This realization did not emerge just out of any doing or just doing any chemistry laboratory. It emerged from labs that were designed to create opportunities for students to design their own problems and find solutions for them—the open-entry labs. In this high school chemistry program only a few labs required careful control of variables. Although tangential to meaning making in school chemistry laboratory settings, I was keen to know what she thought about the curriculum. What kinds of things did her new understanding point to? I therefore asked her, "If you were to write to Alberta Education, what kinds of recommendations would you make in changing high school chemistry now that you are almost done?"

> Ursula: *I think in Chemistry 20 it was almost like a fun thing. It was, sort of, we will go to the lab and go through this today. Chemistry 30 was more clear what the purpose of the lab was and why we were doing them. I think that was a lot more beneficial in terms of education.*

Ursula had mentioned earlier that there had been a lot of emphasis in laboratory report writing in Chemistry 30. "Communication was a big thing in Chemistry 30!" I inquired. ("Yeah, definitely" she replied.) For the purpose of this interview I will classify the activities as open-entry. These are the activities that we did that we just saw on the video and the other type. Do you have any preference?

> Ursula: *I think it's more interesting to do the ones that are sort of open at the beginning. It's almost more spontaneous with the way you are doing them you learn more about scientific procedures because you are forced to. The ones that are outlined at the beginning, exactly how you are going to do it and exactly what to do and how everything should be happening, are sort of very restrictive in a way.*

I wanted to ascertain what I heard. This was an interesting insight that emerged for this student. I needed to know more of what that meant for her. "Do you think you learn more from them than the others?"

> Ursula: *I think the ones that are sort of open at the beginning and you are more unsure of yourself, you learn more because you learn a lot from your mistakes. You learn a lot from asking and if you don't know what you are doing you will ask questions and by asking questions you get to learn more.*

I needed Ursula to give me an idea of what it meant to go through the different steps in both types of activities. "So are you saying that as you go through your own procedure, you may get to understand more the processes, the design of procedure, the skills and the thinking or theory behind your steps?" (Ursula nods) "I am just thinking if I had given you a lab hand out and had outlined that step one do this ---- step two do this --- and step three do that --- and then I was to ask you what were you doing in step two, do you think you would be able to think and describe clearly what you were doing? Or even think about the processes and the theory behind each step taken if at all there was any theory behind that step?

> Ursula: *Probably, maybe after I did the lab and I was looking back on it and if I was thinking about and trying to apply what we have been learning in a certain chapter that the lab was in I could take a guess at what we were supposed to be thinking about at that point. But if its more up in the open and its more you have to do it yourself you have to think about "I should be trying to test this and therefore I won't do this, this or the reverse. The other way when you have the steps set out it comes out like I am* *supposed* *to be doing* *this**!"*
>
> Step so and so! *Exactly! Replied Ursula. You don't even think through what step* this *is.*
>
> Ursula: *Right! You don't have to think about why you are doing it. You just do it. The other way you know what you have to accomplish and you know why and what you are testing and you have to think of a way to test it.*

Perhaps the perceived spontaneity that Ursula referred to had to deal with the naturalness of the problem solving approach that seemed to draw upon students' intuitive knowing. Her understanding pedagogically and epistemologically made sense to me. I realized I could learn more from her by listening to her. Her own language, metaphors, and bodily expressions could teach me a thing or two. She had earlier on mentioned that the traditional laboratory activities were restrictive. From a student's point of view what did that mean. So I asked her, "You mentioned that the activities that have a procedure outlined are restrictive. In what sense are they restrictive?"

> Ursula: *I think they are restrictive because they do not require us to make our own input. They don't allow us to think about the process and why we are doing things. With the others we are forced to think and think seriously about everything we do. We can even be creative because we own the procedures we use. We do things because we think they will work and they make sense to us not because we are supposed to.*

"Wow! This has been very interesting. Thank you." I could not say more. I was overwhelmed by how much Ursula had learned from these open-entry investigations. The depth of understanding of the global picture of science and its practices that emerged for her was beyond what I had imagined. It seemed like a new, complex, dynamic and exciting world of doing-knowing chemistry had opened up for her, first by the realization that she could falsify theories, tests instruments and create her own problems and solve them. Ursula was beaming and willing to go beyond the one and a half hours we spent talking about these experiences. How more complex could a high school student's understanding of chemistry practice get?

To study this complex phenomenon of students' meaning making I was not looking for a specific pattern or a specific or unique answer. I was searching for patterns of activity, coherences and relations in those patterns that could help bring to light students' processes. I needed to be able to articulate these emerging coherences. In the next chapter I will elaborate on how the different enactivist ideas helped me interpret and make sense of the complex and dynamic processes involved in meaning-making by students. An important note needs to be made that in the process of trying to make sense of students' meaning-making processes I also wanted to make sense of my own meaning-making of the research. I therefore marked my own investigative processes and tried to use the same interpretive lenses to try to bring light to the research process as well. The main ideas of enactivism I will use are co-emergence, embodiment, self-referencing, structural coupling and context.

Evaluating or Valuing my Research

I had worked for a full academic year and had come this far with these students and even on the last day of their classes when they did not necessarily have to come to school so many showed up for the electroplating activity. I was touched by this. In addition many had volunteered to be interviewed. They must see something worthwhile in doing this research with me. I felt a need to know what they thought about my research. Being there with them for almost a full academic year as a researcher-resource person, working with them must have in some ways influenced the meanings students made of chemistry. I thought that they would also have formed opinions of my research which could help me learn more about the research. In a way perhaps, I wanted to know if they thought I was listening to them and whether they thought the research was of any benefit to them. Perhaps I just needed to be validated too.

> Researcher: Generally what do you think about this research?
> Jager: I definitely showed an interest in it from the beginning when you walked in here. I thought it was very interesting that you were looking at how students learn in the chemistry area especially. I don't know everything about what you are doing.
> Researcher: Yeah, yeah. No you wouldn't know. I just thought I would throw that in because the purpose of the research is to learn something from you that I could take back to other teachers and say, look, this is what students are saying. These are the challenges they face. How can we better help them? I think that would be worth while.

Juxtaposing often allows us to see relationship and patterns. In considering what students thought about my research and my participation in the class I brought the section of the interview with Irene to allow the two students' ideas to speak to this emergent concern I had. I then asked Irene what she thought of the research.

> Irene: That you are doing?
> Researcher: Yeah, that we have been doing, how did you feel about it? Were you comfortable? Was it a waste of time for you? (Both laugh)
> Irene: No I don't think it was a waste of time because it made me conscious of what I was doing. I think in the lab sometime you just go through the motions; put on a lab apron, yada yada yada. Not only is the camera unnerving but just the questions that you asked us and the question that Dr. Meulenberg asked us helped us really to not only be better in the lab but for us to think critically I guess is the better word.
> Researcher: Mmh!
> Irene: So I think it's a very invaluable thing, I am glad you came.
> Researcher: Thank you! And the fact that you had more than one person did that help? Was it of benefit to have more than just Dr. Meulenberg by himself.
> Irene: I think so (hesitantly). I think I have a tendency not to heed the words of those I am familiar with. But when it comes from someone else I would probably do a double take and think, "Oh, hmm!" "may be!" Yeah, Okay." So it was, beneficial for sure to have a second person around.
> Researcher: Mmh! It is gratifying to know that it made a difference.
> Irene: Because I think there's also a difference in the way that ---
> Researcher: We look at things.
> Irene: Yeah. When one supervising person may see one aspect and concentrate on one aspect the other person may be able to come up with other things. So it is very useful.

Both students seemed to think that my research and my participation in the class were useful. In particular Irene alluded to our (the teacher's and mine) questioning claiming that it not only helped them be better at doing the activities but that it also helped them think critically. Hearing this from the students reaffirmed for me that the context -- the environment is complicit in meaning making. If I was not doing the kind of research that I was doing, perhaps the students and the teacher would not have engaged in the kinds of interactions they did and the kinds of meanings that emerged for all participants about doing laboratory investigations would be different.

CHAPTER TEN

ENACTION IN THE CHEMISTRY LABORATORY

Wanderer, the road is your footsteps, nothing else;
wanderer, there is no pain, you lay down a path in walking.
In walking you lay down a path and when turning around
you see the road you'll never step on again.
Wanderer, path there is none, only tracks on ocean foam.
(Antonio Machado; cited by Varela, 1987, p. 63)

Unlike in traditional science education research, the goal of my research was not to make value judgments regarding whether students' conceptions were misconceptions or not. The focus of the research was not to evaluate the products of their meaning making either but to observe and to document what it is students do to make meaning for themselves. In so doing, I drew attention to and developed some understanding of the processes students used to create meaning for themselves in high school chemistry. According to Maturana (1999) meaning takes place not in the words but in the interactions, in the flow of the co-ordination of co-ordination of behaviour. Put differently Prigogine (1996) said that becoming and/or doing are the necessary indispensable conditions of knowing. My research focused on students' actions-in-a-setting since doing is an expression of their knowing that goes beyond just what they can articulate. By focusing on students' actions I could also observe some of their inarticulable embodied knowing. I therefore made distinctions pointing out what students did in the process of making meaning which can also be described from the enactivist perspective as a bringing forth worlds of significance for themselves (Varela, Thompson & Rosch, 1991).

The Story of My Own Engagements

To prepare for these activities, I made several trials engaging and recording my engagements in classroom settings in and out of class. This was an attempt to get a sense of how I would act and interact, an attempt to determine my own confidence level and to work on my skills at asking questions and at learning to recognize emerging situations that could be used to invite a shift of attention to a different set of particulars.

Several learning moments emerged as I engaged with the students. In the first instance, I could not be fully prepared to know what would happen in the investigations. Interacting with each student was a new experience with a different set of parameters, different understandings, interests and ways of approaching problem situations. My acting evolved with the setting most often triggered by my understanding of the problem situation and of the student's actions and questions. Although one could argue that the chosen problem situations were a preset curriculum, the lived curriculum was significantly diverse for different participants. It co-emerged with the meanings or understandings that developed for the students, the teacher and myself.

Secondly, my positioning as a researcher and as a resource person sometimes raised tensions and internal conflicts for me. Prior to the start of the open-entry activities, I engaged more with the students as someone they could get information from or check their answers with. This tended to define the relationships that emerged. Therefore during the initial stages of the open-entry engagements the students tended to ask questions expecting me to provide them with answers. I also tended to respond to their questions and actions by providing possible answers and not necessarily questioning them to invoke their own answer formulation. Depending on students' progress, I found that I had to keep redefining my role with each situation I was invited into. Knowing that students had a limited time to work on the investigation, when students got stuck and after struggling with their own ideas for sometime I would offer possible paths to follow and leave it to them to decide what resonated with them.

The students did not seem to have the same expectations of the classroom teacher. They tended to want to ask the teacher for opinions and to show the teacher how much they knew. Our roles were different, the history of the development of the relationships were different. I realized that I could use the difference in the relationships to enrich my own research. As a way of gathering more comprehensive data, the teacher was requested to record his engagements with the second video-camera we provided. My engagement and my being in the classroom setting and in the individual group settings gradually changed as I asked more questions. The students and I could work out some problems together. The relationships therefore continued to evolve with the setting.

From my engagement in these activities it is apparent that a coherent understanding of students' meaning making process is possible. However, the processes of developing these meanings are complex, dynamic and evolutionary. They tend to require extended periods of study to allow for the evolution of the relationships and to build enough confidence and trust for all participants to be able to take risks with their understandings. The meanings that students make are also complex and can not be arrived through one-shot paper and pencil tasks. By focusing on students' interpretive processes in open-entry settings, a different understanding of learning chemistry in high school setting emerged for me. Learning chemistry is not only about understanding, subject matter, doing verification laboratory activities, copying and reproducing what the teacher says, doing assignments and passing examinations. It also involves doing complex chemistry learning that involves engaging laboratory activities that extend students' cognitive abilities. In addition it involves entering into, nurturing and maintaining social relationships as well as coming to understand one's cognitive, personal and inter-personal abilities. It is, in a way, a process of identity formation within a cultural setting. Maturana (1999) in his discussions about the biology of love argues that human cognition grows out of love. Human beings, through languaging and interaction create occasions or triggers that stretch the boundaries of our perception and expand our cognitive domain. Because we are all unique, bringing different histories of interaction understanding and coherence to any situation, we offer (in a Maturanian love) triggers that enable us to see things from different perspectives thus bringing forth a different world of significance. In that regard we need to live in relation with others. "Anything that undermines the acceptance of others, from competency to possession of truth and on to ideologic certainty, undermines the social process that generates it." (Maturana & Varela, 1987, p. 247) Love, as the biological foundation of social phenomena, is a stepping stone to interactions. Like every emotion, love is a biological dynamic, or process that brings coherence or meaning to our bodystates in relation to our environment. In this study when we create opportunities for students to enact their knowing with us and allowing the students to exist beside us as legitimate knowers within this laboratory setting, it is an act of love. This understanding has implications for what I do and for what we do as teachers.

Emergence of Chemical Knowing

Johnson (1987) talking on the nature of meaning said that

> Meaning is always a matter of human understanding, which constitutes our experience of a common world that we can make some sense of... *It* is not merely a fixed relation between sentences and objective reality. Understanding is treated as a historically and culturally embedded, humanly embodied, imaginatively structured event. We can not understand the nature of meaning, therefore, without a theory of understanding [or without a theory of knowing] that explains how we can experience a shared, public world. (p. 175-176)

There is a fundamental circularity that enactivism posits as the missing link in our understanding of cognition. Historically, theories of cognition or knowing have focused on the mind-body, thought-action, mental-physical, inner-outer dichotomies to explain their logic. Varela (1987) said "what moves me ... is the swift somersault between the so-called inner and outer, between mind and nature, between rock and bowels. Where do we find here the proud distance between us and it? There is no distance, not even the distance between an it and its picture" (p.48). Although in this quote Varela was talking about the message in the poem he selected to open his writing, the intrigue lies in the way the same could be said of cognition and living and of body and mind. This is the paradox of cognition. The topology of the Moebius strip, (Rosen, 1994) can in concrete ways instruct us and enable us to see that in complex dynamic systems the issues of inner or outer, mind or body are issues that are ontologically temporal. For instance, the distinctions we make are not necessarily the same for all living organisms. They generally emerge from our languaging, our history and our structure as social human organism. They arise from a dynamic of our temporal existence and temporal perception. What at one time seems two sided is at the same time one and everything else in between. To fully describe and understand living is to understand that there is no separation between an organism and its environment (Lewontin, 1991). Organism and environment co-specify each other in perpetual circularity of co-existence. For humans, this mutual specification occurs through a history of continued interactions in language which is the foundation of the social domain. In co-specifying each other and triggering changes in each other, a world of significance is brought forth.

Theories that have been used historically to study students' learning in school science and in chemistry have been dichotomous, a feature that tended to polarize understanding and project a narrow and limited view of the process. For instance, as I indicated in chapter two, several theories of cognition have been posited that focus either on the individual, as in radical constructivism, or the social dimensions (as in social constructivism) of human knowing. Emphasis may be on either intellectual/mental development or emotional/affective changes. These polarizing tendencies have also been a result of over emphasizing either the curriculum or the context or theory or action. Enactivist thought offers an approach that brings all these dimensions of human knowing in the forefront and recognize that all are complicit in meaning making and learning. Its view of cognition as perceptually guided action in which knowing is embodied and knowers bring forth worlds of significance with others acknowledges that knowing is both individual and social. At both the individual and social levels knowing is mediated by action in language as one interacts with his or her own thoughts and ideas or with those of others. These interactions can occur at different levels, for instance, in school learners can interact with others through reading textbooks, through discussing textbooks with others, through listening to lectures, through doing laboratory work and reporting their laboratory work.

When a flow of action-speech-thoughts, a playful lingering with phenomena evolves to become a choreography that experienced chemical knowers along with new initiates can recognize and accept as chemical knowing, a new coherence emerges for all and a world of significance is brought forth. Students like Agasta can in class discussions then make assertions that, "that's how new knowledge is made." The high school students in this study along with the teacher and researcher were able to recognize chemical activity in the investigations of the different activities. In these open-entry investigations, students' chemical knowing emerged out of a dynamic, free flowing, interplay of body and mind, of organism (human) and environment, of thought and action, of reason and emotion and of logic and intuition.

In the next section I will discuss some of the enactive doing in the interactions that were part of the process of meaning making and therefore were complicit, in my view, in the emergence of chemical knowing. These include: feeling, distinguishing, perceiving, languaging, existing besides and validating.

Feeling: A Playful Lingering and Exploring

The open-entry activities involved in this study required student input at different levels. Although initially students were not comfortable with the differently structured, non traditional approach, they gradually came to realize that they had to make decisions. The activities demanded students' curiosity and imagination. Once they realized that the approach was non-threatening and that they were allowed to differ and pursue their own ideas, a safe playful space where they could take risks and explore emerged for some of them. The import of a safe playful space and its impact on personally meaningful learning is captured in Sacks' (2001) early chemistry explorations.

> As a start, I wanted to lay hands on cobaltite and niccolite and compounds or minerals of manganese and molybdenum, of uranium and chromium - all those wonderful elements which were discovered in the eighteenth century. I wanted to pulverize them, treat them with acid, roast them, reduce them - whatever was necessary - so I could extract their metals myself. ... This way I would enter chemistry, start to discover it for myself ... I would live the history of chemistry in myself. (p. 69)

> I spent a good deal of time in the lab (*my own lab at home)* examining chemical colours and playing with them. There were certain colours that held special, mysterious power for me. As a child I had loved strong, bright blue of the Fehling's solution in my father's dispensary. ... The most mysterious and beautiful of all the blues for me was that produced by dissolving alkali metals in liquid ammonia (Uncle Dave showed me this). (pp. 78-79)

The playful explorations, the laying of hands and feeling of the minerals allowed him to marvel at the beauty and mystery of chemistry. It also created for him an opportunity to immerse himself emotionally, physically and intellectually with his chemical world, a world that was not limited to school. This sensing or embodied exploration of chemical phenomena by Sacks is described by Marshall (2003) as a continuing way of Sacks' meaning making of new phenomena. He reported:

> I [James Marshall] let him [Oliver Sacks] touch the sample of beryllia (beryllium oxide) that electronic manufacturers sometimes use for a thermal backplane. "But don't put it to your lips!" I warned, (it's poisonous!" He fondled the piece of ceramic beryllia like he did everything he investigated in nature, lovingly exploring its feel. "It's cold!" he exclaimed. "This is new, I never saw this before!" (p. 879)

By playing, touching, smelling sometimes tasting these chemicals we develop a bodily sense, an intuitive knowing from which we can start to enact and articulate our relationship with them and with our environment. Feeling and playful lingering educates intuition. Another example of creative and yet playful lingering[18] was recorded in

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[18] Watson used in his description of his doing chemistry playful words such as "my doodling . . . on paper" (p.183), "fiddling" (p.180) with models, and "play with a model" (p .201)

Watson's (1968) rendition of the discovery of the structure of DNA. Talking about their earlier explorations to find out how the bases might be arranged Watson said

> I spent the rest of the afternoon cutting accurate representations of the bases out of stiff cardboard. . . . I quickly cleared away papers from my desk top so that I would have a large, flat surface on which to form pairs of bases held together by hydrogen bonds. . . . [I] began shifting the bases in and out of various other pairing possibilities. Suddenly I became aware that an adenine-thymine pair held together by two hydrogen bonds was identical in shape to a guanine-cytosine pair held together by at least two hydrogen bonds. (p. 194)

In the open-entry investigations used in this research, students sometimes were not familiar with some materials for instance some of the metal strips they used as electrodes in the pop-can cell activity or some equipments such as the multimeters. Some were not familiar with setting up electrical circuits. By touching, feeling and playing with the materials their bodies developed a sense of how they could handle and work with these materials. In Salome's own words,

> If you get a chance to play around with the activity, something might pop up in your mind and you say oh this probably might answer it only to find that it may also be a problem to investigate. Just learning theory is boring. (Salome's conversations with the researcher)

Distinguishing Objects

In doing open-entry investigations, students had to manipulate objects. These were at times unfamiliar and students did not know how to handle them. Students had to find ways of coming to know and use them. Objects are ontologically ambiguous; they do not carry a set meaning. Their meaning evolves in action. A common joke about some of our (African) earlier leaders is that when they first visited the Queen of England and were given forks at dinner, rather than using the forks to eat they used them more like toothpicks because there was nothing inherent in a fork that immediately said to them, this is an instrument used to eat. In their history of interaction with natural phenomena, pointed objects like that could be used in a multiplicity of ways that included picking ones' teeth. This ambiguity of objects affords possibility and creates a space for creative doing-thinking-talking. In handling objects we can transform them into whatever instrument we are able to use them for. In his study of experimentation and meaning making Gooding (1990) claimed that

> The ontological ambiguity of manipulated objects is essential to the construction of the new phenomenal possibilities. The ambiguity of what is manipulated is crucial to the creative process because it enables free movement between possible (mental) and actual entities (material). This ambiguity is therefore as essential to thought - experiments as it is to real material ones. (p. 26)

When students first encountered some of the materials, they did not know what to do with them or how to handle them. When they started handling the materials, sometimes playfully lingering with the materials, they were able to develop, with the guidance of the teacher and researcher a working definition for all the unfamiliar materials or unfamiliar aspects of the instruments they used. Students as a result were able to make distinctions for themselves, for instance between the different scales and the different settings of the multimeter. Their playful lingering could be seen as a bodily thinking through doing as well as thinking about doing. As they interacted with these objects they developed a qualitative knowing about the objects that enabled them to act in particular ways that made the objects distinct. Students could then test and evaluate the instruments as well as their own ability to use the instruments. Repeating the test, re-evaluating their skills and the reliability of the instruments all became part of making meaning and developing and embodied chemical knowing.

Articulating Observation and Experience

The students' investigations were always new to them. They had no ready-made ways of perceiving or articulating their experiences. They therefore had to invent ways of transforming these experiences and making them more concrete, vivid and shareable so that they could remember how they perceived the interactions and be able to build on them. In Salome and Joanna's case, for instance, at the beginning of the iodine clock reaction, they had not anticipated any problem with transferring solutions. They thought that they could just pour out the solutions and wait for the reaction to occur, which they did as a starting point. As the activity unfolded, they came to realize that they needed some way of marking consistently when to stop pouring the solution and when to start timing it. The question of consistency in both the amount of solution poured out and timing became important. They therefore had to find a way of marking and labelling that point where they would stop the adding and shift attention to some other point in this flow of speech-action-thought.

This labelling as Mason (2000 p. 12) put it would enable students "to capture and trigger a certain way of looking (*acting-speaking-thinking)*, a particular stressing and consequential ignoring," as they would then have to ignore any other droplets left in the measuring cylinder once they reached this mutually agreed upon point and move on with the investigation. They initially used the word "dump," implying pouring all of the solution at once to try to capture the empirical meaning of their action. A problem emerged with the last few drops. How long do you let them drip? What could they do practically to maintain consistency? It seemed common-sensical to dump and hold for some time. They therefore invented other working terms: "dump plus one," "dump plus two," and "dump plus three". For Salome and Joanna, these working definitions allowed them to control their actions, by being able to articulate what they were doing or what they intended to do. They could now jointly formulate ways of modifying and further exploring this emergent phenomenon. The students could now also start to interpret their actions using this language they had created.

Inviting Acts, Inviting Gestures, Inviting Utterances: Triggers

In these activities, when one person asks a question, for instance Saskia asking me whether they have to pour out some solution at the start of the iodine clock activity, this triggers different reactions in the people involved. Their chemistry and structure are changed. The context or environment is also changed. First, in this case based on each person's understanding of the problem situation, there is a different expectation for both Saskia and I. The anticipation and delivery of my response triggers structural changes for all participants in different ways. The utterance of my response also triggers changes in the dynamics and direction of the interaction and in so doing brings forth a different world of significance. In one way, my response could either satisfy Saskia's enquiry or not, triggering, in turn, different structural changes in both of us. How Cees responded was also co-determined by the moment-to-moment changes in the direction and dynamics of the interactions. All these interaction were mediated by emotions. In a loving, nurturing environment, Saskia was not intimidated by how everyone reacted and interacted; a space was created for her to enact her knowing beside us. She asked questions until she made sense of her own world.

Existing Beside Others

> From here Griffin [*the book he was using to help him do his chemistry*] moved (and I with him) to "sympathetic inks," which became visible only when heated or specially treated. I played with a number of these ... all this was fun but it was chemistry too. (Sacks, 2001, p. 72)

Sacks' (2001) quotation illustrates how through interacting with the accumulated body of chemistry presented in the chemistry books that were available to him he learned about sympathetic inks. He also learned from what his family taught him about what they already knew. His existence beside others gave rise to the various meanings of chemistry that emerged for him.

> I loved the yellowness, the heaviness, of gold. My mother would take the wedding ring from her finger and let me handle it for a while, as she told me of its inviolacy, how it never tarnished. … My two older brothers Marcus and David … Uncle Dave would teach me about metals with little experiments. He loved to handle it [tungsten] – the wire, the powder, but the massy little bars and ingots most of all. "Feel it, Oliver," he would say, thrusting a bar at me. "Nothing in the world feels like sintered tungsten." My parents and my brother had introduced me, even before the war, to some kitchen chemistry. (Sacks, 2000, pp. 3-64)

From his youth, Sacks lived and interacted closely with people who strongly influenced him, and his world. His family, both immediate and extended nurtured the youthful curiosity he had about the world around him. The people in his life always invited him to look at phenomena in different ways, enabling in the process a shift of focus in which new and different worlds of significance emerged. This, in turn, transformed him as he acknowledged "I had been living (it seems to me in retrospect) in a sort of sweet interlude, having left behind the horrors and fears of Braefield. I had been guided to a region of order, and of a passion for science ..." (Sacks, 2001, p. 313). Oliver Sacks' experience is an example that may persuade us to see that existing besides others influences the meanings we make and the worlds of significance that arises for us.

In this research, existing beside others was critical for students' meaning making. The teacher, the student teacher, other resource persons who occasionally came to our laboratory, other students in the class and I were part of that context in which students made meaning. In different ways we influenced the meanings that we all derived from these open-entry investigations as we, in interaction, invited each other to shift focus from time to time to different ways of looking, seeing, touching and interpreting and in the process bringing forth different worlds of significance for us. Often the ways we invited each other to shift focus included offering prompts both in action and language. We needed to engage in conversation to be able to see and recognize this invitation. In inviting each other to look at things differently we expand each other's domain of cognition. We also expand each other's domain of cognition by being each other's external memory of shared experiences. As a collective, we exist as an infinite wealth of memory for each other.

Existing besides others enables us to co-create as a unit. For instance students' joint manipulations of physical objects enabled them to be creative and to formulate new ways of doing, thinking and talking about phenomena. In our interactions we also validate each other or legitimize each other and each other's actions. Students' learning from the teaching validates the teaching.

Validating Acts

Meaning making in open-entry activities involves various dynamic cycles of validating. In this research, validating occurred at various levels for different people. All participants, sometimes working together in small groups and sometimes individually, engaged in acts of validating processes, setups results, and meanings of the results at different stages of the investigations.

In the technological problem solving in which students created a physical product students had to make sure that that product worked hence students' repeated concern about whether their setup worked. The criteria of validation were established in the physical manipulation of the materials which often gave students the necessary feedback to validate their actions. Emerging from that was also a concern about what the results meant. With these concerns most often students, working together with an experienced other negotiated the criteria of validation.

The teacher, and I and occasionally other resource persons present also engaged in acts of validating. Students often invited us through questioning to validate their initial problem solving ideas. Other times the teacher or I initiated the acts of validating, for instance when Dr. Meulenberg asked Salome and Joanna at the beginning of their pop can cell investigation the series of questions about what they were doing and what variables they were working with. This not only validated for him that the students had a workable plan but also for the students it allowed them to think through their plan and get validation from the teacher. The initial individually originated act of validating students' ideas by an experienced other was transformed into a teacher-student unitary propagated process. Often the experienced other in their teaching roles validated students' actions for instance checking what materials, or what chemicals or what instruments students chose and whether they were handling or using them appropriately. In other words they checked whether students' action-speech-thoughts were viable.

Validation occurred through all levels of the investigative process. Criteria for validation in this community were negotiated between students or between the students and an experienced other.

Languaging: A Necessary Ingredient

For students to make meaning of these open-entry investigations, they needed to talk to each other, to the teacher, to the researcher, and to the existing body of chemistry in textbooks and other literature. The learning environment in these investigations was conversational. Students engaged in conversations about their investigations bringing to bear some of their lived experiences as they interacted with each other and with the activity. To be able to make decisions about what to do, how to do it and why, students shared ideas and negotiated their actions sometimes with the help of either the teacher or the researcher. This set of experiences amplified what goes on in a normal laboratory, occasionally to a lesser degree. Students sometimes used words that in science have specific agreed upon meanings in ways that they thought were appropriate. Within those settings this usage was not problematic as the meanings of the words arose from the context. In that sense they developed their own language a language that would not make sense if removed from the context. The example given earlier on of Salome and Joanna during the iodine clock investigation developing the "dump plus one," for instance, illustrates how students had to find precise ways of talking about their particular action so that they could decide how to use its completion as a mark for starting timing. They invented their own language. A portion of the documented description of the interaction is presented below.

> Teacher: So, tell me before we start, I am going to start the stop watch...?
> Salome: When this thing (pointing at the solution in the measuring cylinder held by Joanna and indicating where the dumping will take place) is dumped in.
> Teacher: when? ... There is a whole bunch of "whens" there.
> Joanna: (Both students laugh as they recognize the ambiguity-in-action of the statement) Ok. Let me talk. You start timing when I finish pouring this thing in and then you stop when the whole thing ---
> Teacher: Finish pouring it in?
> Salome: Yeah, finish pouring it in.
> Teacher: Now hang on, does finish mean the "dump' or the "drops"?

Through conversation and action students negotiated what it was they would do as the meanings of their action-words were clarified by them in the doing. Coupled to this negotiation of meaning, was also negotiation to co-exist and in that co-existing to co-contribute to this interaction and to the meaning making. Joanna pleaded with Salome to let her talk and to help clarify to the teacher what they meant by finish. The context as well changed as it became, through language and action, more accessible and more precise.

Although most of the conversation recorded within a group focused on how to find a workable solution to an immediate problem as the investigation evolved, a significant level of the conversation within and across groups was social in the sense that students talked to each other not only to help each other find a solution to their problem but also to maintain social relations. When students from one of two groups that had been working beside each other sharing instruments through the course of their investigations suddenly shout in a playful singing voice, "we found it first, we found it first", it is not to seek help or to offer help to the other group but to create a space where the students can continue to talk and maintain the social relationship that has been established as they worked separately-together beside each other. Although the primary goal of the conversation may have been to find solutions to the investigations, in working towards a solution, the social dimension of maintaining relationships was not neglected.

Learning, and meaning making in these high school investigations was also a social activity. Talking or languaging in the process of making meaning in high school chemistry is not merely a reflection of previously or currently existing logical thoughts about chemistry. It is also a means of formulating or giving form to the internal body-states resulting from the interactions in the form of ideas, emotions and actions that are complicit in the emergence of the world of significance brought forth. A complex world evolved that is not only academic but also social, historical and dynamic. In other words languaging is an all-at-once activity that brings together the past and the future into the now, acting-in-the-moment.

Relation With the Physics of Instrumentation

The students' experiences with instrumentation in these activities were significantly educative. Students were at the start unsettled and needed a lot of help learning how to handle and use the equipment. It seemed like the more sophisticated and multifunctional the equipment was, the greater the tendency there was for students' discomfort and the greater the time it took for them to figure out how to use it. Most of the students had not used a multimeter before. A significant amount of time was spent learning how to use and read the multimeter. However, for students who used simple ammeters and voltmeters less time was spent teaching students how to use them. Students developed meaning from experience.

Their learning became more meaningful to them when it involved physical manipulations involving bodily sensed knowing. As they spent time, with the help of a more experienced other, playing around, turning this and that knob, fitting this wire here and another one there, they began figuring out how the equipment worked, and gradually became more confident in what they were doing and were able to successfully engage the activity to a workable solution. The other observation with instrumentation was that some students seemed to feel that not only did they need to know how to use them, but also to understand the physics of how the equipment works. Their rationale was that when they got stuck they would know how to test whether the problem was due to malfunction of the equipment or not. Students were not given much detailed instruction on the instruments which could be seen as a flaw in our teaching. However, this apparent instructional flaw was fruitful for students' learning as it created for them an opportunity to engage the instruments meaningfully. As they played around with the instruments they developed embodied knowing-how and also a knowing- that-I-can. Because they could learn how to use the multimeters themselves, they became more self-confident.

The use of equipment in the pop can cell activity and the electroplating activity was further complicated by the fact that students had to interpret circuit diagrams and translate them into investigative set-ups with unfamiliar electrical equipment. The activities seemed to increase in complexity and difficulty as we moved through the series. Students found it highly challenging to set up parallel and series circuits in the electroplating investigation even with a circuit diagram in front of them. The pictorial representation was no where near the real thing. As chemistry continues to progress and new measuring instruments and other more sophisticated equipment is developed and introduced in high school chemistry, there seems to be a need to pay close attention to how it is introduced to students. Because of large amounts of work students have to cover in high school chemistry, there is a tendency to for teachers to teach students in great detail how-to for efficiency. The dilemma that this presents is that it takes away the opportunity for students to learn meaningfully by themselves.

The lack of experience with the equipment and the designing of procedures, for some students, were frustrating. However, it seemed rewarding for students who were confident or who developed confidence as the activities evolved. The task in these activities seemed to be able to make the students recognize that their intuitions were worthwhile and that those intuitions were important in taking risks in learning.

Directness and Indirectness of Evidence

Chemistry involves making judgments about observation. Where do we look? What do we look for? Do we need to measure? What is it that can be considered as relevant informative observation? Having made observations, what do they tell us? In other words what are they evidence of? Are the observations direct evidence of A or do we extrapolate A from theory, for instance how do students know that the change in colour in the equilibrium reaction activity is evidence of completion of reaction? Are the main reacting species, we are interested in, responsible for the colour change or have we introduced into the system other ingredients that would cause a visible change from which we can make inference about the reacting species? How much of this do students understand? Do students need to know it? Most of these questions in high school chemistry classes are addressed by the teacher who has more experience with chemistry. This study showed students making observations and sometimes not knowing what to do with or how to interpret the observations so that they could become part of the descriptions that students could own and share. In all such cases, similar to Sacks, students called in a more experienced adult to help them make sense of the observations. Two examples from the iodine clock are when Peter and Paula were negotiating and trying to interpret their results. They had to have the teacher as part of the context of this negotiation. The second is when Salome and Joanna were trying to determine what the end-point of the reaction was. The end-point colour change was not a direct result of the main reaction being timed, but a reaction with a secondary additive that could react only when one of the reactants was used up. Whether students knew that, was irrelevant because they did not know or even have to know what the reacting species were. These students called on the teacher and the researcher as they worked to resolve this.

Uncertainty/Tentativeness

Most students were, in the initial stages of each activity, very uncertain of what they were doing or what they were supposed to do. In most cases, until they had actually carried out one or two trials or test, when asked what they were doing or how far they were, they could not clearly describe what they were doing. Their answers and actions were hesitant and they tended to consult more with each other and with the teacher or the researcher until they attained a certain level of confidence in their own judgments and actions. When the teacher made an announcement, say for instance if he discovered that students were asking the same question over and over again or they were not able to use instruments properly he would stop and address the class about the issue brought to his attention. In those instances if the students were still not clear about their investigation they would stop and listen, however, if they had already figured out what it was they wanted to do they did not stop what they were doing to listen to the teacher. If they did stop it was for a very brief moment and they carried on with their activity. So in these cases the students depended on each other and on both the teacher and the researcher to help clarify the purpose of their own interactions.

In the interview both Joanna and Salome, for instance, revealed that although they were not very comfortable with uncertainty, they could handle it and work with it until they developed a clearer understanding of what they were doing. Their message was that once you understood what your investigation was about, it was easier to become actively involved. They thought the iodine clock activity was simpler than the pop can cell activity and therefore it drew them in quicker. With the pop can cell, Salome and Joanna took a long time to figure out what they were doing and to get it to work and because of this they were not drawn into the activity that easily. They actually expressed some negative feelings about it in the interview because they did not like to work with electricity and therefore were not addressed by the problem enough to be excited about it. Although I did not ask them, I got a sense that there was, perhaps a culturally gendered influence to this which determined their sense of identity. As young women, they are not expected to know anything or be excited by anything that required them to play around or understand electricity.

Sometimes the objects and instruments students used were unfamiliar and students did not know how to use them. Maturana argues that the reality of things or as Heidegger says the thingness of things is defined or exists in their use. When students started using some of this unfamiliar equipment, with the teacher or researcher beside them, they gained meaningful experience on how the instrument could be used. In using it they defined for themselves what it was and therefore with several successful attempts using it they developed confidence in using it. Towards the end of class, in most cases, students did not need either the teacher or researcher to be able to use the equipment.

Uncertainty allowed students to stretch the boundaries of an immediate problem as they played around in thought and action with what in the moment was significant, familiar or of concern to them. They asked questions, sought help and in doing this, students incorporated new ideas and interests to address challenges that arose moment by moment from the situation. They brought forth significant situation specific knowing for themselves through interacting with others and with phenomena.

Theory and Action of Chemistry

Theory and action in science and especially in chemistry are intricately interwoven. There is circularity in the ways they interact. Theory has enabled scientists to transform the physical world we live in and likewise scientists' actions have transformed the theories they developed to explain their experiences with the physical world. Two views that show the relationships of theory and action are presented in the following two quotes: one from a chemistry educator, Lagowski, and the other from Sacks.

> Chemistry has always been a practical discipline. The invention of bronze—an alloy of copper and tin—represents an important event in the evolution of the chemical arts because elemental tin is not found in nature and to make bronze requires the winning of tin from an appropriate ore followed by alloying procedures. Now that's chemistry in a modern sense! (albeit with little theory). Still that's the way much of chemistry has developed historically—without much theory to guide it. (Lagowski, 1998, p. 425)

> What actually occurred in these processes, however, was not understood. There can be a deep practical knowledge, Uncle said, long before theory: it was appreciated, in practical terms, how one could smelt ores and make metals, even if there was no correct understanding of what actually went on. (Sacks, 2001, p. 41)

Theorizing About Action without Action: Only a Theory?

The discourse of theory and action in chemistry is a discourse of human in(ter)ventions and interpretations. To be able to translate theory into action we have to be able to make interpretations about the behaviour of phenomena. We have to have an embodied knowing about phenomena that would enable us to make these interpretations. These interpretations reflect our confidence in the way we make sense of phenomena and the assumptions we make as we make distinctions about our experiences with our world, for instance, what is it that we consider a chemical reaction? How do we know it gets to completion? What is it that we define as completion? In making meaning for themselves students also grapple with this discourse at their own level.

To create meaning for themselves students had to define their own problem spaces. They had to interpret and make sense of information provided to them to help them create a problem statement that they could understand and fully engage. From this study, most students initially worked individually in defining the problem statement for themselves in the preparatory phase. However, when they had to translate their interpretation into action, they found that they had to redefine the problem statement and negotiate what it is they were going to do because what they had thought of previously was not enough to get them started. Without the materials or objects of investigation and the actual interactions with these materials, their judgment about the reality of the activity was most times inadequate. Some students were able to modify and work with their original classroom based ideas. For instance in one student's reflective notes she wrote:

> Before I went to do the experiment I assumed I'd be manipulating the current and time (high current/less time). Once I tried that in the lab, the key became over plated; the surface was rough, the colour of the key was black. Then I decided to dilute the solution and poured 40mL of water to 60mL of the $CuSO_{4(aq)}$ solution.

> The end results were just as I hoped. After I finished the lab, I was glad when I finished first and proceeded with excellent results.

They often had to modify their initial ideas because without the actual manipulations of physical phenomena their ideas or prior theories were just theory. Some students had a problem interpreting and translating into action what 'getting the reaction to occur in 20 ± 1 s' meant until they actually did the first trial and noticed a change. They had no way of anticipating what the end-point was. Students needed the empirical hands-on access to even determine with their peers and the more experienced adults in class what it was they would accept as evidence for the complete reaction.

Structural Coupling

When organisms including human beings are structurally coupled to their environment their history of recurrent interactions give rise to patterns of changes for both the organism and its environment that may be recognized as structural congruence. The two mutually specify each other. The diagram below (Simmt, 2000) illustrates the schematic flow of interactions. Both person and environment co-specify the interaction and they in turn are changed through that interaction.

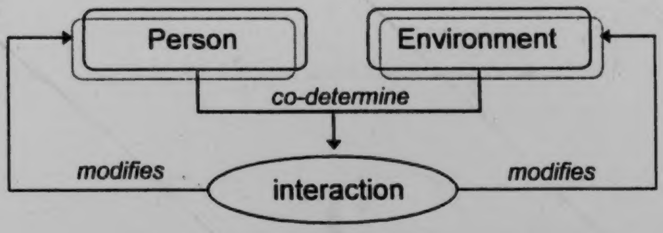

Figure 16. Structural coupling arises as recurrent interaction between person and environment.

In this research, examples of this can be seen with all three students interviewed. Ursula, for instance was changed by the new meanings that emerged for her from her interactions. She became more confident. She could think more critically about science and about her doing science. She was also more philosophical in her views about learning and about knowledge creation. Her world also changed. Chemistry laboratory investigations were no longer "just a fun thing to do." They had become something to engage something through which one could view their world. In her words, "By doing these experiments and testing theories it's the best way to learn and get new theories, new knowledge". When making claims about connections it sometimes resonates more when one can find similar connections existing in other situations. The following example with Sack's (2001) personal experiences with migraines may help in the sense that he being a medical doctor articulated this phenomenon by even relating it to his medical condition. He in retrospect wrote that the influence of his migraines on his perception and especially on perceptions of colour may have contributed to his inclinations later in his life. By this, Sacks, perhaps, is alluding to his work in neurology from which emerges many of his writings[19]. His personal explorations with colour and photography enabled him to recognize the connection between these explorations and his physical condition. He described his own episodes of migraines as games of his brain. "I started to look forward to my occasional attacks, wondering what might happen in the next one (no two were quite the same), what the brain, in its ingenuity, might be up to. Migraines and photography, between them, might have helped to tilt me in the direction in which years later, I would go." (p. 143)

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[19] Sacks' books include *The Island of the Colorblind* (1996), *Seeing Voices* (1989), *Awakenings* (1974), *A Leg to Stand On* (1984), *A Man Who Mistook His Wife for a Hat* (1970), *Migraine*, (1970).

In the open-entry investigations, the interactions that ensued allowed students to be structurally coupled to their environment creating a history that only they embodied as they worked. This interaction not only transformed and moved the investigation forward it also changed the working students. Whereas initially students were unsure and hesitant in their speech-action-thoughts, they became more and more confident with the progression of their investigation. Students became expert knowers of their investigations. They could make decisions or choices and direct their investigations to a point that only they could clearly explain and justify their research journey.

Depending on where students were at, coupling occurred at various levels. For some students, the investigations were a means to an end and not solely an end. The investigations challenged these students to take the process further and to actually think and talk about their own thinking and learning. Here, the students were now removed from the activity, but could take the activity with them, kind of step a little distance from their own thinking, and think about their own thinking processes, their knowing and their roles as knowers. At this level students were coupled to their thoughts through language. These were some of the students who were able to evaluate the entire process and tell me whether they thought doing investigations like these were of benefit or not in high school chemistry curricula.

CHAPTER ELEVEN

COHERENCES

Coherences are patterns of meanings or patterns of embodied relationships that emerge from our experiences. These coherences enable us to distinguish entities and to connect or relate them in ways that make sense to us. We are born into relations. We live in relations. We see in relations. We think in relation. In making meaning we distinguish because we see relations. Being able to see relations is our mode of making meaning for ourselves. Coherences are not written in stone or unchanging. They may emerge as a result of interactions that occur at different levels including the physical, intellectual, emotional and spiritual levels. Maturana in his interview with von Foerster (The American Society of Cybernetics, 2000) spoke of coherences as patterns of relations. In academic research, for instance, what one reads, where, how, with whom influences these emergent coherences. Coherences that emerge for me may be different and are of necessity different from what somebody else may see because we all bring our history of physical existence, interaction and cultural existence to what we perceive. What I see is determined by my history and the context under which it takes place and therefore changes simultaneously for me with my continued evolution and with the continued evolution of my environment or context. This continuous process of change or evolution does not negate the existence at that time, of the previously made coherences. This goes to show the temporal and groundlessness of our existence and yet it does not negate our existence. It points to our dynamic living-in-the-moment nature of our perception, our cognition and therefore our very existence. This dynamism leaves traces of memory in the body that experienced phenomena. These memory traces at times act as the link between our cognising body and the new experience fostering the emergence of the resonances or coherences. Recognizing coherences in students' meaning making and in my meaning making may enable me to speak to the emergence of that meaning.

Coherences keep emerging for me each time I view the original videos or the video clips I made from the originals. They also emerge each time I write about the videos or my experiences with the students, the teacher or when I review what I have written about these experiences or discuss with colleagues about what I have written or what I perceive as we share our research experiences from time to time. Needless to say that even in my interactions with my family and friends I can not escape from finding coherences that have a bearing on this research. Writing, therefore, emerges as a way of making coherences to ourselves and others we interact with, the coherences of our experiences.

Classifications emerge from our making distinctions. They are contextual tools we create and use to make meaning for ourselves and to organise our understanding of our world. When taken out of context, they have a tendency to oversimplify issues and remove or minimize the essential complexity that they were intended to capture and organise. Because the process of researching processes involved in high school learning and meaning making is at its infancy and the language of description is not fully developed, I have for the sake of clarity categorized some of these emergent coherences into two main groups: coherences relating to the processes students used in finding solutions and those characterizing the relationships that emerged from those interactions.

This classification is not exhaustive and other classifications can emerge from the descriptions and interpretations offered.

Coherences in Students' Processes

One aspect that repeatedly came up in students' actions was their hesitancy. Students most often were not certain about what to do and how to go about it and this uncertainty seemed to be played out as reluctance or hesitancy. Some students expected that there would be one distinct right way of approaching the problem that the teacher or researcher could help them with, hence the repeated questions "is this they way we are supposed to do it?" or "how are we supposed to do it?" Students had different notions of what it was they were doing and what it was they were supposed to do. An interesting observation was that even when students had done a lot of preparation before the lab, they still had to make a lot of decisions on the spot as they came to know their working environment and what materials were available. As part of the process students had to build or create a problem to investigate.

Building or Creating Students' Problem-Solving Spaces

In all the activities we did, students were given the same hand out as a prompt for their investigations. They were also given the same instructions regarding preparation for the activity. Students created their own problem-solving spaces based on how the prompts given made sense to them. These problem-solving spaces seemed to co-emerge with the investigation and were expressed or enacted in the different approaches, processes and solutions students developed.

The building process could be described using cyclical pathways. There was no one common pathway used by students. However, in each cycle there seemed to be four main phases: the planning phase, the testing phase, the evaluating phase and the synthesizing phase. Embedded in each of these phases were processes that seemed also to go through cyclical trails in which students would create, test, evaluate and synthesize. The reiterative process featured at this level as well since the manipulation of objects in these settings provided immediate feedback and allowed immediate reflection and evaluation on the processes, the skills, the materials, the evaluations, and the syntheses done. Building their problem solving spaces through these phases was not a linear process where students planned, tested, evaluated and synthesized and the building was complete. Instead students went through complex creative processes involving sometimes several non-linear reiterative loops and pathways. Students could start with one notion of their problem. They would test it, evaluate it and use that evaluation to synthesize and determine the next turn in this pathway. At first glance it could seem just from the description that the cycle of building would be complete only to find by looking closely that in any of these steps there could be a twist or a problem that require students to stop evaluate, test, re-evaluate, re-synthesize and change direction.

Decision Making

Students commented that because most of the details of the investigations were left to them to determine, some of the students initially felt incompetent to make those decisions since traditionally the decisions were made for them. Students had to make decisions about:

- Whether the approach they chose was viable, if not, what alternatives could they try?
- The sequence of progression and the criterion for the choices they made

- What variables were significant
- How to formalize and interpret their observations
- How to analyze their observations
- How to evaluate the process and the products of their investigations
- What and how to communicate to other members of this community of knowers

In making these decisions students assumed or had to assume a position of knower. This did not mean that they know with certainty but that in the process of living or co-existing with others in this community and within the high school chemistry culture the know how to interact and act adequately to co-expand each other' cognitive domain. Therefore they were no longer just recipients of knowledge but originators of their knowing as well. They could make contributions in different ways to the meanings that emerged. Students had to develop investigative skills that allowed them to act and behave adequately in their new role. From these open-entry laboratory investigations, the different investigative skills students learned included knowing:

- What materials to use, how to use them and the quantities to use
- How to operate the instruments
- What variables to investigate and how to investigate them
- How to formalize and interpret their observations
- How to transform observations into supporting evidence
- How to evaluate the instruments and their effect on the evidence.

Uncertainty

These are some of the areas of the investigations in which students had a high degree of uncertainty. With so many diverse and qualitative decisions to be made at different stages of the investigations, the approaches used were bound to be diverse. As Maturana (1999) poignantly stated it, "the release of certainty opens up the world. Knowing with full confidence is the enemy of reflection." (Maturana, 1999 p. 5)

When we let go of our certainty, and we allow ourselves to see things differently, we create for ourselves an opportunity for re-birth and a chance to live life differently. Certainty tends to limit perception. Uncertainty on the other hand opens up possibilities for new ways of seeing things. It allows students to stretch the boundaries of an immediate problem as they play around in thought and action with what in-the-moment is significant and/or familiar to them. In doing this students incorporate new ideas and interests to address challenges that arise moment by moment. It creates opportunities for surprise and renewal. Uncertainty in learning creates for the learner opportunities to see and to try different things thus expanding their domain of cognition. Many students, in their interviews, acknowledged that because they had to make a lot of decisions themselves, they were forced to be actively involved and to think seriously about what they were doing. Every sentence, phrase, utterance and every action in the interactions was not trivial since it determined the flow and direction of the sequence of events. Every action, every word uttered, every reaction of the environment acted as a trigger for all participants resulting in the co-emergence of different actions and ideas about the flow of the investigation. The activities evolved with time. Students learned chemistry by setting chemistry in motion, using their own ideas and doing things with chemistry and being surprised by their own creations rather than adopting the routine step by step procedures that have been used over the years. It is our present lack of understanding of the role played by uncertainty in learning that prevents us from coming to grips with the concept of co-emergence.

Doing Chemistry as a Discursive Practice

Learning or cognition is a natural non-linear process that happens to us. Learning depends on teaching but it is not determined by it. The processes involved in the learning through doing of chemistry were found to be reiterative. The feedback loops inherent in doing, manipulating objects or creating a physical entity offered students immediate opportunities to reflect-in-action, about the action and about-self-interacting. Students could on-the-spot think of ideas, find procedural ways of testing them, test the ideas and the operations and obtain immediate feedback about their actions and their ideas.

Students found that they had to keep "going back and trying different things" engaging the same steps over and over again, not linearly but in a cyclic fashion. These steps involved: identifying an emergent problem for which they had to find an answer through physically manipulating objects, designing and testing a procedure to solve the problem, interpreting and evaluating the feedback or results followed by a synthesis which at times brought forth a new problem/sub-problem which needed to be solved to pave way for the solution for their initial problem. Other times, the synthesis established trends that enabled students to move closer to finding a solution for their initial problem. This cyclic iterative process can be illustrated by the diagram in Figure 17. The entire process often involved going back and forth between the initial problem and the emergent sub-problems if the initial problem statement was not changed. Because students could change their problem statement, even with the new problem statement there was a constant back and forth movement within the cycles of investigation to evaluate whether the process was getting students closer to their main problem solution.

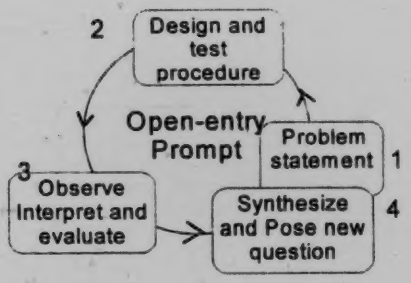
2
Design and test procedure
Open-entry Prompt
Problem statement
1
3
Observe Interpret and evaluate
Synthesize and Pose new question
4

Figure 17. A cyclical iterative model for students' open-entry investigations.

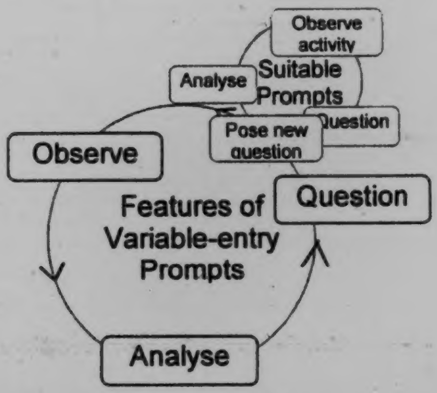
Observe activity
Analyse
Suitable Prompts
uestion
Pose new question
Observe
Question
Features of Variable-entry Prompts
Analyse

Figure 18. Fractal model for observing research process where new questions call previous ones forward into consideration (Simmt, 2000, p. 39).

The cyclic iterative model gradually became multilayered and more complex as new problems nested within the main investigative problem emerged and the cycles of designing, testing, interpreting, evaluating and synthesizing multiplied. Figures 19 and 20 also adopted from Simmt (2000) can be used to represent this evolutionary complex and dynamic process. To present a complex fractal like picture.

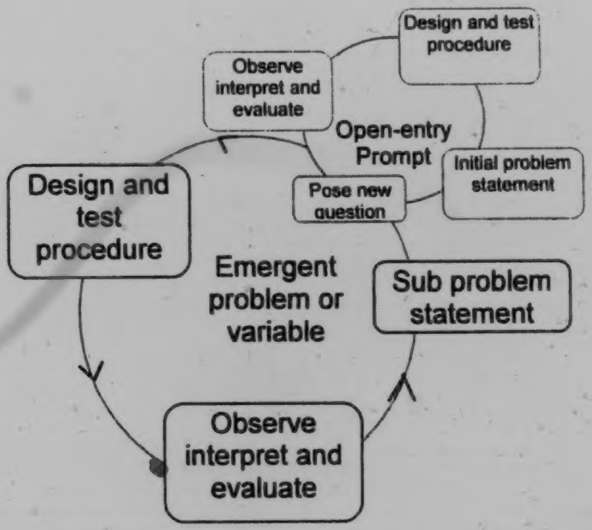
Design and test procedure
Observe interpret and evaluate
Open-entry Prompt
Initial problem statement
Pose new question
Design and test procedure
Emergent problem or variable
Sub problem statement
Observe interpret and evaluate

Figure 19. Second-level iterative open-entry investigation model.

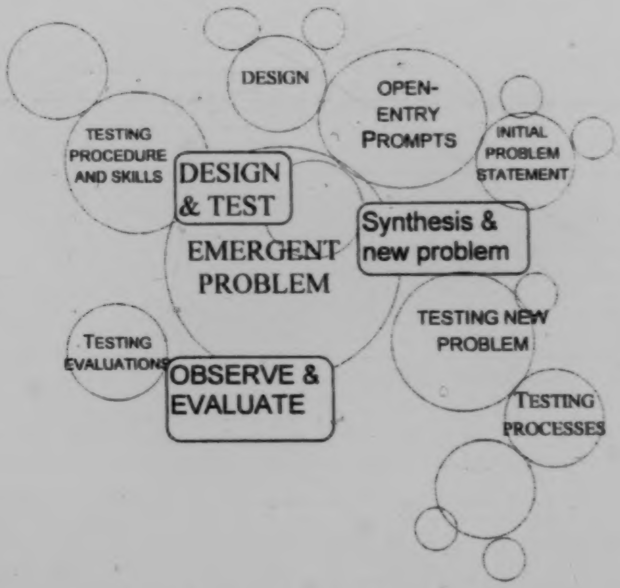
DESIGN
OPEN-ENTRY PROMPTS
TESTING PROCEDURE AND SKILLS
INITIAL PROBLEM STATEMENT
DESIGN & TEST
Synthesis & new problem
EMERGENT PROBLEM
TESTING NEW PROBLEM
TESTING EVALUATIONS
OBSERVE & EVALUATE
TESTING PROCESSES

Figure 20. Dynamic nonlinear model of meaning making in open-entry investigations.

Not only did doing chemistry teach students about how to work with objects but also how to work with others. In many respects the processes that students engaged to solve their problems were very similar to the processes I engaged in doing this research although this research is not about me manipulating physical objects. The self similarity described by Simmt's (2000) Fractal research model can be observed in both my research and the students' investigative processes. Figures 17 through to 20 illustrate this.

Coherence in Relationships

In this study students worked mostly in pairs. Pairing of students was voluntary. Because of the different histories and styles of interactions that each student brought to their group, several different patterns of interactions emerged. These could be characterized by the following features:

- Some pairs chose to collaborate fully including in the pre-lab preparation where students came to the lab with well developed tables for recording results
- Others found ways to somewhat divide the labour; Jason and Rami, for instance, where Rami recorded results while Jason manipulated the equipment
- Others worked in parallel especially in the pre-lab preparation phase and developed separate investigative designs that they compared to decide what procedure to follow.
- Few worked individually and shared their results with the teacher, the researcher and sometimes with other groups Ursula, partner, Jager. This mainly occurred with the iodine clock investigation. In the latter investigations students worked with others in pairs, threes or larger groups especially with the electro-plating activity.

Student-Researcher Relationships

When I approached a group, students either invited me in to their investigation sometimes by asking me a question or checking with me whether what they were doing was right. Other times they just ignored my presence as if I was not even there. The latter often occurred when students felt they knew or were certain of what they were doing. Students were not obliged to "perform" for me because perhaps I did not have any significant influence over how they were graded. Whenever they accorded me "any" power, was when they needed some information that they thought I could provide. On the other hand I knew that I wanted the students to be free to explore and to find as much as possible their own ways of finding solutions to the problems posed. So as much as I could, I tried to tease out of them answers to their own questions without necessarily imposing my ideas. In that role I had to assert students' authority and offer back the power of knowing to them. A subtle but significant difference in the ways students interacted with me was that they seemed freer to engage their social interactions in my presence than when their teacher was with them. The flow of their conversations whether social or otherwise tended not to be interrupted by my presence whereas with the teacher there seemed to be a switch. They had to be seen to be preoccupied with the investigation or the chemistry more in the teacher's presence, a relic perhaps of the traditional school practice where students have to show the teacher how much they know.

Student-Teacher Relationship

All students in these three classes respected Dr. Meulenberg, their teacher. It seemed that they always paid attention when he talked even when they did not seem to follow what he was saying. Salome and Joanna in the pop can investigation had heard him say "and you divide by one hundred." They kept this in their mind although they did not really know what the teacher meant. They later came to realize what he meant and referred to his earlier comment. Dr. Meulenberg also respected them. He did not dismiss their ideas or in any way make them feel negative about their ways of doing things. He gave them their space when they needed to have the space, for instance to think through and test an idea or the space to come at a later time to re-do the investigation. During his discussions with them he listened carefully and engaged students' ideas thoughtfully.

In these open-entry activities students seemed to want to display for their teacher how much they knew. It seemed also that they wanted to learn more from him and therefore they readily engaged with him in their interactions and conversation about the interaction. This could perhaps be because he was the one in charge of the class and its organization and they tended to call on him for this or for that.

He was quite accessible to his students which made the students trust him. They knew they could depend on his listening and attending to their concerns. If a student suddenly needed to use something he had not provided for the activity he would always try to get it or to find an alternative; he allowed that kind of flexibility and spontaneity.

Having had several decades of experience working with high school students in science, Dr. Meulenberg was very comfortable is his own skin so to speak. He was relaxed with the students which made the students also relax. Students also seemed to trust and take his word seriously. In this class Dr. Meulenberg could freely enter students' turf and students would be comfortable and welcoming to him. Students seemed to trust that his interventions would lead in ways that would bring them success or perhaps that his presence would validate their actions. He seemed sometimes hesitant to direct students and wanted students to come naturally, through their own interactions and thinking, to certain ways of seeing. In this sense he was a facilitator, shepherding students towards certain directions.

He seemed to model to his students ways of dealing with uncertainty as he would confidently try new ideas with them even when he was not certain of the outcome. This along with his flexibility, his open-mindedness and his extended intuitive pedagogical knowing enabled many possible pedagogic relationships with his students.

Relationships between the teacher and students seemed to have no issues about power or authority. They all seemed to have well established roles and ways of working together. The teacher and the students seemed to know and accept that they learn from each other in these investigations. Their relationships were trusting, respectful, and collegial at times and friendly.

Student-Student Relationships

In general students tended to relate with each other with respect, as co-equals. Whenever students working in a group came across something they were not familiar with, they consulted each other as if to find out what the other knew about the new phenomenon. With a few exceptions, they discussed their ideas amicably and tried out each other's ideas when the ideas were deemed reasonable. There were however, a few incidences where due probably to one group member's choice not to engage the activity that there was evidence of student-student power imbalances. The student who had done the required homework or who felt he or she knew what the activity was about tended to take the upper hand and lead the group. In that case, the student tended to give instructions, assigning who would do what, when and sometimes how. Sometimes as in the case of Jason and Rami, the student who had the knowledge and power to direct the activity, Jason in this instance, virtually took over the actual manipulation of materials leaving the partner, to record the results. An interesting pattern of interaction was observed between Liz and Becky in the electro-plating activity. Becky who claimed not to know what she was doing, and what series and parallel circuits were, did not seem disempowered by that lack of knowledge. She participated confidently in the investigation, voicing her ideas and sometimes testing them as they went along. Liz, who seemed to have a somewhat stronger conceptual understanding of electricity, did not take that to mean that she had the upper hand. Instead she created a space for Becky to also enact her knowing and together they directed the investigations.

Group-Group Relationships

Most groups tended to work independently except when both members of a group were stuck or not sure of something that the teacher might have alluded to. They either checked with the neighbouring group or with either the teacher or the researcher. The interactions in that case were of mutual respect. At times groups shared equipment and groups made an effort to give each other enough time to use equipment. There was however, a situation between two groups, one female the other male that did not quite fit the description. Although portrayed in a playful manner, the displayed behaviours by both groups reflected some power struggle. Jason and Rami who were sharing a multimeter with Priscilla and Maureen made a lot of noise, bragging about their results and taunting Priscilla and Maureen to get better results than theirs. In return, Maureen whose group had obtained the multimeter first, decided to give the young men an ultimatum using the multimeter. When the two women eventually got their results and the results happened to be lower, Jason and Rami could not keep quiet about it. They made the young women know that their results were lower than theirs despite the fact that the other group already knew.

Cultural Gendered Relationships

Cultures differ in the ways they value men and women's work or voices. Women and men as a result tend to see themselves through these filters. Science education research is replete with studies that show how science historically has been biased toward men. Science in the west is seen as a masculine subject. The students in this study live within a culture that expects men to do well and to take risks in a science classroom. Some of the patterns of interaction in this investigation can be interpreted from this view point. The behaviours described above displayed by Jason and Priscilla's group may be a reflection of different culturally engendered roles. The two women who are from a non-western cultural background, seemed to expect to perform just as well as their male counterparts opposite them. They, instead, were taunted by their male counterparts who seemed to expect that the women would not perform as well as they did. The young women's low voltage readings seemed to escalate this competitive and somewhat antisocial behaviour. I am taking the liberty to dwell a little bit on this five minute period of the interaction between the two groups because during my discussion with the various graduate student groups, several people remarked on it. The two male students were noticeably noisy and taunting once they obtained a high voltage reading from their investigation.

Another interesting pattern of interaction that could, perhaps, be understood as enacting culturally gendered roles is that between Cees and Saskia. Sometimes these nuanced roles are paradoxical for women creating for them identities that can be in conflict. Saskia, a young curious woman who seemed intent on getting her way at times, worked with Cees in all the activities including the project. Both the pop-can cell activity and the electro-plating activity involved using electricity. Saskia, in both activities, tended to defer most of the physical interaction with materials and the articulation of the outcomes to Cees proclaiming that she is not comfortable with this electricity stuff. This distancing from electricity could be explained as a cultural gendered positioning because electricity can be seen as a masculine domain. In activities where they mixed solutions, the softer and may be female-friendly science, she wanted to be recognized as a competent knower. A typical instance of this behaviour was observed during the group project activity by the river. Saskia and Cees were testing the river water with different water quality test kits at one of the picnic tables in the park. For a moment while Saskia was working on one of the tests, Cees left the table to go and pour some of the waste solution they had so far accumulated in a larger waste disposal bottle at a different table. On returning Cees asked her a few times how she had carried out the test. It appeared that for Saskia, the questioning was about her capability as a woman. How dare Cees question her ability to count drops and mix carefully, this was a woman's domain. She retorted in a stern voice "I am not incompetent you know!" an answer that showed a struggle for power and recognition. For a brief moment Cees was speechless and he quietly sat down beside her and in more sober tones they continued to work together.

Joanna and Salome reported that they were not comfortable with electricity. Their discomfort emanated probably from the fact that they viewed electricity from a gendered lens. Electricity is culturally seen as a man's domain and that view may have played itself out in the ways students interacted with phenomena. They were not confident in the ways they interacted and the meanings they derived out of those activities that involved electricity were rather fragmentary. This was revealed in the interview. This suggests that the students' meaning making in high school chemistry is not separate or divorced from the larger cultural milieu but that the culture informs meaning making. It is one of the lenses through which we make coherences of our experiences.

Co-emergence: Laying Down a Path in Walking

> What we do is what we know, and ours is but one of many possible worlds. It is not a mirroring of the world, but the laying down of a world, with no warfare between self and other. (Varela, 1987, p. 62)

The creating of meaning is a co-emergent and embodied process. By this I mean that both the knower and the known emerge together in a relationship where the knower and the known co-specify each other. For instance the example I gave in chapter six of Saskia coming to the iodine clock reaction unprepared and uncertain of herself and gradually becoming more self-confident and assertive as she experienced some success with the investigation or in chapter seven of Jason creating his powerful cell and commenting that he was not dumb after all, speaks to this co-emergence. Saskia for instance, started the activity questioning many aspects of Cees' interaction. In a sense she was not part of the Cees-Saskia unit. But as she started interacting a Saskia-Cees unit emerged which transformed the investigation from one that was initially only about testing volume to one that included size and shape of the reaction vessel. In turn she became a confident knower who offered ideas about where to take the investigation. In creating meaning, we do not step out of the world and contemplate it. Saskia could not remain as a separate entity and hope to know what the activity was about. She had to immerse herself in and interact with her partner to develop that embodied knowing. Rather we participate and come to a realization of how we are part of it and how we can not remove ourselves from it. We learn to live within our world as an integral part of it. In other words we come to realize how the world is as much a part of us as we are a part of it. Co-emergence allows us as knowers to realize that our knowledge of things, not just their names, arises from our relating with them. As we interact with them we develop bodily meanings which may be visual, tactile, emotional, intellectual, and spiritual or any combination of these. By interacting within our world we re-create ourselves and our world bringing forth a new world of significance and in doing so we expand our cognitive domain as we create new spheres of possibilities.

The worlds of significance brought forth by different students spoken about in chapters six, seven and eight, through their interactions in the various activities are strikingly different. The worlds of significance brought forth through Saskia and Cees' interactions at different stages in the evolution of the activities differ significantly, for instance, from Salome and Joanna' worlds of significance in that not only the meanings derived from the activities differ but also the paths they walked were different.

The ways the two groups entered the activity, what they did to address the question and what they left with after the activity were totally different. Both students and teachers could not have predicted the shape, form and direction their investigations took because with both groups there was a certain level of hesitancy and tentativeness at the beginning of the activity. Both groups had a struggle with deciding what to do at the beginning and how to proceed from there. Saskia, unlike Cees for instance, struggled with conceptualizing or visualizing the form the activity could take simply because she had not prepared for it. Salome and Joanna on the other hand seemed to have had an idea how to start but struggled with deciding when they had completely transferred one solution into the reaction vessel and also when the reaction was complete and how to maintain the two variables consistent. For both variables, the decision was made through interacting with the materials and with the teacher. By developing their own language-of-action ("dump" or "drops" or "the edge of something is easier to determine than the middle of something") in action students laid down a path for themselves to move forward. Students developed a sense of consistency and control in their action. The students' previously vague utterances changed as they were now able to put form and direction into what they wanted to do. Their level of confidence too increased with every bit of success they achieved. Both knower and known were transformed and co-emerged through interaction. How did students feel about their meaning making in these activities from my perspective? The students became more self-confident with every little success they experienced and gradually learned to trust themselves as their own resources and also as their own agents for their learning. In both the in-class interactions and interviews, the students indicated that they felt fulfilled as knowers through some of the investigations.

Students' Embodied Knowing

Neurological studies (Damasio, 1994; Sacks, 1987, 1996), cognitive science studies (Maturana & Varela, 1987; Mingers, 1995) and studies on evolutionary embodied philosophy (Lakoff & Johnson, 1999) suggest that in human cognition, knowing happens to us. "We do not freely select what enters our consciousness" (Davis, Sumara & Luce-Kapler, 2000, p. 19). We function most of the time intuitively. Our body it would appear from neurological studies is our first contact with our world and since it is an enactive knowing, living body it interacts with its environment selecting what it chooses to interact with before we are even conscious of it. Damasio (1994) presents this complex interaction between body and mind (brain) using the metaphor of a master, perhaps, and his body guard. The brain acts as a body guard who according to Damasio, follows the body, "detects the threat; conjures up a few response options; selects one; acts on it; thus reduces or eliminates risk." (p. 223) Therefore in interactions our bodies develop rudimentary bodily senses, meanings and knowings of phenomena that are diverse which act as background reference for consciousness. Through what it knows, the body allows us to transform and create our environment and us. The body informs consciousness of possibilities, possibilities that sometimes consciousness acts upon allowing these acted-upon possibilities to surface to the level of logic. Other possibilities however, remain as traces embedded in the body and sometimes surface as intuitive knowing or as emotions. The students' interactions with objects develop embodied knowing which may transform these ambiguous and unfamiliar objects into instruments that they can work with. Students' emergent embodied knowing came through for them in the open-entry investigation allowing them to learn how to use unfamiliar objects and equipment and to develop procedures and processes that enabled them to successfully find solutions to their problems.

In these investigations, for instance, students sometimes came to the investigation not very certain what they would do. Although students may not have been able to predict the direction the open-entry activity would take nor the meanings they would create from it, when they started working with the materials, they started developing bodily knowing that allowed them to develop a sense of where they could take the investigation. While working with others they started realizing the different things they could do. Because most of our learning is not conscious, students developed an embodied sense of where to take the investigation, whether it was to test the equipment, to find out how others were using it or to simply figure it out by themselves through explorative trial and error. Jager for instance realized by testing their multimeter with a dry cell of known voltage, that it was a good way of checking whether their multimeter worked. They could therefore know whether they were getting the pop can lid to conduct or not.

Feeling of Reticence vs. Efficacy

A seemingly interesting paradox was revealed through the conversations with students about their interactions. Many students were not immediately forth coming about their progress. When asked how they were doing, they either deferred to each other to verbalize what they were doing and in so doing said nothing until the researcher or teacher suggested a way out for them by diverting their attention from themselves and their actions to their results or they would say that they did something wrong even though when a more experienced person was to look at their result they would see progress. It seemed that students' initial uncertainty led to low self confidence which sometimes emerged or could be seen as reticence or reserve; an uncommunicativeness that seemed to protect or cover up one's sense of self. In the iodine clock reaction activity, for instance, when the teacher started asking them about their result, because they could not explain the result, Paula seemed lost for words. Peter, on the other hand, immediately said "I think everyone messed up," as if he felt that they were ineffective. Some students did not seem to know how to interpret their results, what to expect or that success is negotiated within communities of knowers hence their immediate tendency to suspect their performance without checking with an experienced other in this community. They were therefore surprised by their own progress or success at times after discussing with either the teacher or the researcher. Other times students could judge their own success based on the performance of their creations such as the pop can cell. In this instance students were able to determine their own criteria of validation. In the experience of

Jason and Rami with the pop-can cell activity, before they could even successfully read the multimeter, they knew their cell was working because it had caused a considerable deflection of the multimeter needle. That way they could validate their own action. They however, were faced with the challenge of negotiating and setting other criteria of determining the best cell. Several possibilities that could have been used included that the cell produced high voltage, high current, was aesthetically pleasing, easy to assemble, economic or eco-friendly. Jason and Rami's success in getting their pop-can to work and produce high voltage was such an emotionally charged learning experience that made Jason utter his self-evaluative proclamation that he was not dumb after all. Dewey (1934) had insight into this aspect of learning: "Learning and knowing involves emotionalized thinking and self-evaluation in which there are feelings whose substance consists of appreciated meanings and ideas" (Dewey, 1934, p. 3).

Much of learning depends on the inner bodystates of the learner as the primary creator of personal meaning or the main participator in the process of making meaning. What these felt bodystates meant for the students sometimes was expressed as fear of risking one's ideas or as questioning the rationality of the self. Some students alluded to this during the interview when they mentioned that they questioned how their brain works. This questioning may point to the student's realization that the activities required them to change the ways they have been doing chemistry. As Irene put it "It extends your mind beyond what is given". So in trying to deal with this challenge they have to get in touch with themselves and try to make sense of their personal inner workings as well. This is an example of critical self-evaluation which also points to the enactivist notions of embodiment in knowing and cognition.

Risk Taking

We create when we discover and express *and/or extend* an idea, artefact or form of behaviour that is new to us. Our discovery of what has been revealed by others is still a creative achievement *for ourselves* (Keller, 1996, p. 3).

A useful aspect of meaning making and developing ownership of the process in these open-entry activities involves risk taking. Students had to take risks and try out their ideas during the investigations. Students who were able to initiate ideas and follow through with them seemed to develop more satisfaction and confidence out of the activities. They learned to realize more importantly that their ideas were valued in these investigations and that they could make a contribution in solving a scientific problem. Some of the students even commented that if people did not try out their ideas there would be no new discoveries.

Decision Making

With traditional laboratory activities, decisions were made for students about most all aspects of the activity including what to measure, how to measure, what to look out for, what steps to take. The open-entry activities on the other hand, left many more of the decisions to students. Students initially tended not to make decisions on their own, they needed guidance. In most cases they wanted to know what they were supposed to do or whether what they were doing was what they were supposed to do. They seemed not to trust their own initial intuitions and judgments about things so they consulted the teacher and me. However, when they had experienced some success or seemed to be more in control of what they were doing or at least had a sense of direction they started to make their own decisions or consulted each other more. In many cases during the investigation, students had to go with what they felt was right because we could not be with all the groups all the time. Gradually their decision making process improved from one activity to the other. They realized that they could rely on themselves and on each other and therefore started to take risk and try out their own ideas.

Irene, Ubbo, Salome, Joanna, Ursula and Yager all alluded to their intuitive feeling of whether what they were doing was right or wrong. From the interviews, the students mentioned that they gradually became more confident as they experienced success. In addition students, like Veronica and Agasta, who came to the laboratory well prepared and confident tended to make more decisions on their own. Their confidence enabled them to take risks and try out their ideas. Students were able to make decisions individually and in groups and find workable solutions for their problems.

Confidence Building

During the activities I saw students' confidence gradually grow as they realized some progress; for instance, students gradually relaxed and took control of the direction of their investigations, although I could not tell to what extent and also how it impacted their learning. It was in the interviews when they were not rushing from class to class that students revealed to me the value of these activities. Jager mentioned that with open-entry activities, "You reflect more because you don't just have your analysis to reflect on and whether you have result but you also have basically your own creation to reflect on." In Ursula's view "It's almost more spontaneous … you learn more about scientific procedures. The learning from these open-entry investigations was "invaluable" to use Irene's word. It offered students an opportunity to see themselves do their own chemistry and to see how far they could take it. To see their ideas valued and validated made them feel confident. Students were validated as members of the learning community.

With this confidence students could openly voice their opinion about the high school curriculum. They suggested that it should incorporate more of the open-entry type activities, not to the exclusion of the traditional ones they cautioned. They all seemed to realize the important learning potential these activities had for them. It seemed from the interviews that the activities had a potential to address the multiple human dimensions that feature predominantly in learning and meaning making. These include; the personal (including predispositions), the cognitive, the cultural (relationship), and the products or artefacts.

Creating a Path in Walking

Doing science and in this case chemistry, is a creative human endeavour. It involves naturalistic problem solving which draws on intuition, on others within a community and involves all bodily knowing. It is about structurally coupled human beings struggling with their ideas and their problems of describing and explaining phenomena they interact with in their daily living. It involves processes that co-emerge with the situation, ever unfolding and bringing forth new possibilities. It is therefore not predetermined and can be seen perhaps as creating a path in walking.

> Science seldom proceeds in the straightforward logical manner imagined by outsiders. Instead, its steps forward (and sometimes backward) are often very human events in which personalities and cultural traditions play major roles. … That is not to say that all science is done [in the same manner or] in the manner described here. (Watson, 1968, p. xi-xii)

Chemistry elucidates some of the complex relations that we have with our universe as we understand it. It also postulates as part of this universe, our living within this universe, sharing interacting and exchanging matter and energy as integral parts of this universe. It enables us to understand how we can also be seen as organisms that are adapted to function and live in this universe. Human beings are not only of the earth, with the earth but also go back to the earth. Chemistry can be used as a tool for understanding ourselves and our environment. In understanding chemistry we do not only get to know ourselves but we also create possibilities for living differently.

Complexity of Students' Meanings

Meanings that emerged for students were complex and multifaceted. Although the interviews recorded in chapter seven could be seen as summative and therefore address the big picture, epistemological as well as ontological questions concerning students meaning making, looking at the overall students' interactions allows us to see how the local meanings arising from interactions in the activity could give rise to some of the global meanings that emerged for some of the students. The depth and breadth of students' conversations reflect this complexity.

Some of the meanings, especially the self-referential meanings allowed students to relate and learn about themselves where students could so to speak step aside of themselves, observe themselves learning, listen and interact with this other learning self, reflect on the learning of the other self and return to talk about themselves learning. Students were able in the interviews to talk about these personal and intra-personal meanings pointing us to the seriousness and level of engagement they experienced.

Students' meanings also brought me to the realization that they learned a lot about interpersonal relations. These meanings were often expressed in the ways students interacted with others. Students listened to each other, to the teacher, to the researcher and in return offered in both action and speech responses that alluded to their listening to others.

Students' interactions could be seen as one public expression of their knowing about interpersonal relations. Although one could argue that one need not undertake these kinds of investigations to develop this knowing how-to-act, for students to develop skills and embodied ways of knowing how-to-act in a chemistry research setting, working as a team, consulting others for further clarification or for sharing of ideas and for negotiating processes and interpretations students had to be immersed in this kind of activity. Other public meanings that arose from this research are meanings about the entire process of doing chemistry and communicating their findings with other members of the community such as the teacher and the researcher. Students learned how initiate, design, plan, and carry out their own investigation. In addition they learned how to make decisions in non-linear, reiterative chemistry problem solving processes. They also learned in an embodied way how to evaluate all these processes and to write laboratory reports of their own problem.

Emergence of a Fully Embodied Knowing Student

Until I interviewed students I knew that many students had exhibited in their interactions and in their writing of both the laboratory reports and the reflective notes gradual changes in their dispositions towards engaging open-entry investigations. Students seemed to have gradually become more confident in the ways they approached the uncertainty and complexity of these investigation. They seemed to find the activities interesting and challenging and they did not avoid the challenge. They persevered and worked with each other even when they felt frustrated. They repeatedly expressed in their reflective notes that they enjoyed doing these activities. They liked them because the activities allowed them to be creative, to make an input in the investigation, to test their own ideas. They liked the sense of ownership that emerged with doing these investigations. This perhaps emerged for them because they had an embodied knowing that they originated the ideas, the procedures, the processes and the products of those investigations. Although not articulated in these words, students knew in an embodied sense that they were knowers. They were the experts of their investigations.

The extended interviews gave me more insight into this as I started to realize the complexity and depth of meanings that had emerged for these students. Students could articulate some of these complexities. From their articulations I gleaned their pedagogic, epistemic and perhaps ontological inclinations. These spontaneous articulations were creative on the spot expressions of perceptions or world views. These pointed to the emergence of a fully embodied knowing student who knew and appreciated his or her role in the processes of making meaning and bringing forth their world of significance with others. This emerging embodied knowing student could also see possibilities where once there were only obstacles and a student who knew and appeared ready to act upon those possibilities.

What Has the Research Taught Us About Students' Laboratory Work?

Arguments can be raised by some curriculum developers, educators and teachers that students cannot work effectively in laboratories to:

- create and recreate investigative problem statements
- design and redesign problem solving strategies

- select and reselect materials and equipments to use
- to create and recreate procedures
- learn how to use equipment themselves
- evaluate and re-evaluate materials, designs, procedures and skills
- evaluate equipment
- falsify authority

From this research students were able to demonstrate a significant level of proficiency in undertaking the challenges they encountered to make meaning for themselves. This included doing all the above listed possible impediments. Whatever initially seemed impossible for students opened up possibilities for them to learn more about the process of doing investigations, about the phenomena studied and about themselves. Often in selecting laboratory activities for students, teachers tend to choose activities that would present students with few difficulties. As teachers we tend to over test, remove what we might be problematic and offer to students an almost finished and polished product – a closed type of activity. We solve the problems for the students. What this research suggests is a need for a careful balance between removing possible obstacles and creating opportunities for engaging learning. In fixing procedures, spelling out every detail including use of equipment, we may run the risk of removing possibilities for exciting and engaging personally meaningful learning for students. The question is that do we as teachers fix too much for students? Are there things that perhaps we should choose not to fix when selecting or designing a laboratory program or curriculum?

The question of uncertainty has traditionally been treated as a purely mathematical concept in high school chemistry where it was introduced as a feature of measurement. The students in this study had an understanding that uncertainty was not limited to measurement. Although sometimes apprehensive about it, the students recognized that uncertainty in the doing of chemistry is part of the process as well as the product. We discovered that introducing a degree of uncertainty in the process of doing chemistry was essential for students' meaning making. The uncertainty that arose from giving students a chance to make the decisions about the process prompted students to stop and think seriously about what they were doing. In many of the instances students were compelled to engage others to help them in their thinking processes to clarify the problem statement, to make decisions about the approach to use, the instruments and reagents to use, and how to use them. In addition they needed others to help make decisions about what direction to follow. If they had to change course, students felt compelled to discuss with their partners and either the teacher or the researchers why and how. In many instances, students had to determine and define what "works" in their problem resolution. In that sense introducing this kind of qualitative, process-oriented uncertainty in students' problem solving helped students to seriously engage and think about what they were doing in chemistry. This gave students a chance to experience a sense of the uncertainty inherent in the practice of science and the need for scientists to test concepts to the limit and even to falsify them. The students in essence learned that it is possible to falsify process as well as product.

This research demonstrates that when students, the teacher and I were engaged in investigative chemistry activities, our activity was not limited to just chemistry. It involved also personal, social and cultural domains of our lives. Our whole being was involved and transformed by the experience. Not only the way we each looked at high school chemistry and chemistry learning but also the way we looked at chemistry as a discipline, and the way we looked at ourselves changed. In interactions we brought forth worlds of significance with others and in doing so we also brought forth ourselves, with different perspectives and different dispositions. With this transformation not only is our perception changed but our cognitive domains have changed and opened up new possibilities for us as we anticipate our future.

CHAPTER TWELVE

IMPLICATIONS OF THE RESEARCH

The image of high school chemistry internationally is not at all golden. Many high school students opt out of chemistry because of its reputation. Often students do not stop to find out what chemistry is or what it entails because school chemistry gives only a very limited and rather unpleasant view of it. Chemistry in schools is often characterized with copious memorization, low achievements and/or failure. What is chemistry that students should care about it? The CBA chemical systems II version (1976) starts,

> Chemistry is what chemists do. ... In the industrial chemist's world many chemists make things: propellants for rockets, fuels, fertilizers, plastics, medicines, insecticides, electroplating solutions for putting chrome on car bumpers, dyes for coloring nylon and aluminum, textiles with new properties, gasoline additives to sell to petroleum companies, adhesives to make things stick together, coatings to keep things from sticking together, coatings for paper to make it more opaque, finishes for paper to make it more transparent, waxes for shining shoes or motor cycles, soap to advertise on soap operas, hair for wigs, foaming agents to put off fires, fuels to start charcoal fires, fillers to put in rubber compounding mixtures, antioxidants to keep tires from deteriorating, catalysts to make many processes go faster, inhibitors to slow down corrosion and deterioration of chemicals, perfumes, hairsprays, and shields to solve rocket re-entry problems (p. 1).

The 27 year old list above describes only a small section of what industrial chemists do today. There are thousands or probably millions of other chemists whose activities are not included in the list. Chemistry has grown tremendously so that even the traditional disciplinary divisions (i.e., organic, inorganic, physical, and analytical) do not fit. Chemists of today can vaguely be described because their work has no strict allegiance to one structure, their work is cross disciplinary, for instance there are chemists who study: material science, electronics, non-equilibrium systems, replication, self-assembly, energy conversion, the environment, mesoscale chemistry, sensors, specificity, and seeing at the atomic scale to mention a few sometimes not so obvious areas (Ball, 1994). My graduate study in chemistry was one of those, bordering between environment, forestry, organic and phytochemistry. I can never describe what I did with out referring to the Eastern Canadian Forest, spruce budworm, and endophytic fungus. What coherences has this brought to my understanding of chemistry? A new world of significance emerged from this experience that shaped the coherences I made and continue to make. Perhaps if students were given an opportunity to live the complex, multi-dimensional world of today's chemist they might develop a different understanding of chemistry. How can I characterize the experiences of my graduate chemistry work, juxtaposing them with my high school chemistry experience both as a student and as a teacher, to inform this study?

My Chemistry Background

The graduate chemistry I studied did not require any complex mathematical background. It did not require me to memorize or use elaborate abstract concepts. Most of it was empirical and involved learning skills that often could only be learned by doing. For the first year I was more of an apprentice working with senior graduate students who were involved in similar research. I learned painfully that, in the laboratory, books, journals or other scientific reports could not help me decide how to carry out the research; they did not deal with the particulars of the research. Only experienced people who had carried out this kind of research and had some intuitive bodily knowing how-to-act could teach me. By working with and beside them I learned how to do this research. Several research teams made up of graduate students and professors worked on different projects. The majority of students worked on synthetic organic chemistry projects while my project involved extraction, isolation, structure elucidation (determination) and eventually synthesis of some of the metabolites we identified. Searching for naturally occurring bioactive metabolites from other organisms, fungi in this case, was challenging. I had to learn how to handle very small amounts, how to separate, purify and perform a series of tests with amounts less than one milligram of material. I learned how to use sophisticated spectroscopic instrumentation like nuclear magnetic resonance (60 Hz and 400 Hz NMR), infrared (IR), and ultra-violet (UV) spectrophotometers. I learned how to read and interpret data given by this instrumentation as well as that given by mass spectrophotometers without necessarily understanding the theory of how these machines work. I knew enough to be able to know which protons are downfield (shielded) and which ones are upfield (deshielded), and I could identify and explain the splitting patterns. I could also explain why a proton could either be shielded or deshielded. I could recognize the chemical environments that the protons were in using the spectra that we obtained which allowed me to determine the structures of the different metabolites.

A significant part of the graduate work also involved keeping abreast with the latest developments in chemistry research, reading journals, giving seminars about some of the latest developments. This way I came to know why the discovery of the "bucky ball" was so exhilarating. I also came to know of artimisinin, an anti-malarial drug long used in China, and how it was successfully synthesized in laboratory. A whole new world with many "new" compounds like taxol, palytoxin, zocor, tagamet, and their derivatives came into existence for me. Struggling with synthetic mechanisms, what catalyst to use for what reaction types, knowing the reactivities of different functional groups, and how to protect and deprotect them, all started to exist for me. A different understanding of the politics of patents, pharmaceuticals and natural products also emerged for me.

High school chemistry hands-on activities and for that matter undergraduate chemistry had taught me to rely on cook-book type laboratory manuals. We were always told what to do and sometimes how to think or how to fake it. How many of us remember "cooking" our results in that Parry laboratory manual during our first year at university? Even when we extracted caffeine from tea in our undergraduate organic lab it was always step by step. Of course back then we had no sophisticated spectroscopic instruments, so melting point determination and description of the shiny white crystals was all we could attribute to this compound and no more was said about it then to make any difference to my world.

My experience of high school chemistry I described in chapter one does not preclude the fact that the experiences we had were tightly controlled and directed towards finding the right answer that either the teacher knew or was provided in the teacher resources. We did many exciting chemistry things but always with detailed instructions provided or with the teacher's well structured demos. It is no surprise, now that I look at it, that the realization that no book or journal could help me do my research was painful. Part of high school chemistry was spent on quantitative problem-solving, especially stoichiometric problems. In the undergraduate chemistry program, I can vividly remember how we struggled with chemical kinetics and equilibria. Calculations involving properties of gases, entropy, free energy and electrochemistry were difficult. Physical chemistry was always a problem because of the amount of mathematics involved, the determination of free energy, and entropy of reactions to name a few. Apart from my teaching experience, I have never really had to do so much mathematics in chemistry and yet with my graduate degree in chemistry I consider myself a chemist and have done things using chemistry.

I would argue that as much as my high school experience helped me become the chemist I think I am, my graduate work in chemistry made it all the more meaningful for me. I can now appreciate a bit more clearly issues about the nature of science. I know that chemistry is complex, dynamic and creative. I also know what contributions individuals make to the body of chemistry and to the dynamics of our lives. I also know that chemists are not born chemists; they are nurtured to become chemists. Students in our schools can also come to appreciate this and schools and individual teachers can help make this possible. The activities used in this study have all the qualities that can be used to invite our students to shift focus from the given to the possible.

Pedagogy

Education is in the business of directing students' attention and influencing their interpretive processes. These processes involve invitations to students to shift focus and develop new ways of seeing and perceiving. It seems that "Educators have been rather slow to appreciate the implications of recent insights into consciousness and perception." (Davis, Sumara & Luce-Kapler, 2000) In this research study, students have demonstrated that they are able to successfully handle and work with complexity. Students have complex and sophisticated ways of making meaning for themselves, meanings that are multilayered and that indicate that they know more than what classroom practices offer them. They are able to simultaneously make global meanings through specific localized interactions and conversely make local meanings through global and more generalized interactions. In my interviews with students, students demonstrated this free movement, this free flow from particular issues of investigating the iodine clock reaction to big picture epistemological issues of how knowledge is made and from big picture issues of school curricula to specifics of learning and critical thinking in a chemistry laboratory investigation.

Implications for High School Chemistry Teaching

This research shows that for students to develop personal meaning about the chemistry they do in high school they need to have a significant degree of autonomy in the designing, carrying out, interpreting and communicating of the results of the hands-on laboratory activities they do. Students need to learn how to make decisions about the investigative process including how to ask a research question, how to develop that question into a workable hands-on investigation, how to deal with different variables, how to collect information and evidence, how to interpret observations and results, and how to communicate the findings. They need to be involved in the whole process to be able to develop a fully integrated organic understanding of the chemistry so that they can use it for their own growth. Although this seems like I am suggesting a complete overhaul of our high school laboratory practices, I am not. Students indicated that we need to introduce some features of open-entry to the laboratory activities we have. What we need to think of, perhaps, is a small gradual evolution.

As some of the students interviewed indicated, high school chemistry should include both open-entry type and traditional type activities so that they can get to see how “progress in chemistry is made.” A lot has been said in science education circles about the need for curricula reforms. Part of the argument is that high school science needs to reflect the interrelatedness of science, society and technology. In addition high school science should be engaging and relevant to the students as well as effectively teaching students about the nature and history of science. The main argument used to justify this is that teaching science from a more holistic perspective would result in a scientifically literate citizenry.

A lot has been learned from the curricula reforms of the sixties, seventies and eighties which reflected the nature of the discourse of science and education of the time and also the perceived academic structure of the disciplines of the time. As human beings, we can only work with what we have and what we know to find out about what we do not know. We have now reached a point where we need to shift our paradigm or broaden our view because we have previously learnt that:

- science is not static and therefore one curriculum can not live for ever
- learners are more than just sponges, they can do more than soak up and regurgitate what they are given
- learners are different and have different curricula needs therefore one size does not fit all; science is not defined by academic research scientists only even they would disagree about the perceived public image of science emanating from the experiences of school science
- science does not begin nor end in the school, it impacts our whole existence including how we see ourselves in relation to our environment
- science evolves and out grows the compartments that we would like it to fit into. Chemistry especially has out grown the organic-inorganic-physical-analytical straight jacket

- laboratory programs value structure and are designed to be time efficient to fit in the school structure (hence the recipe-type bias).
- concepts are noticeable but they are not all easy to define, therefore structuring our curricula based strictly on abstract conceptual structures or principles may be limiting.

It could perhaps be that "the mind of a person who is learning a new science, has to pass through all the phases which the science itself has exhibited in its historical evolution" (Sacks, 2001 quoting Cannizzaro, p.155). It appears that for students to develop fully integrated and personal meanings of school chemistry investigations they need to go through the cycle of learning to handle and work with complexity and uncertainty enough times (e.g., through open-entry laboratory activities) to develop the confidence to handle these situations by themselves.

In this study, students successfully made meanings and solved problems in chemistry starting from a somewhat insecure and uncertain positioning where at times they came into the laboratory not knowing in detail what they were going to do. The absence of a detailed procedure in itself was a useful trigger that started students thinking what it is they were going to do. Because there were no certain ways of doing this chemistry students had to be creative and learn on the spot to survive. They plunged in and soon enough realized that they needed to interact with others to start negotiating meaning at various levels. For instance, where students came into the laboratory without a defined problem or problem statement they needed to talk with their partner, or with the teacher or the researcher to start learning how to float.

There was observed progression in students' confidence, independence, acceptance of uncertainty, playfulness, decision making, relationships, and appreciation of the meanings that evolved and processes that evolved.

Teachers deal with uncertainty in the classroom often, but because of the teachers' experience and the ways the uncertainty is handled students sometimes do not realize it. In general teachers tend to reduce students' uncertainty by providing them with answers. In this uncertainty was dealt with differently. Students were encouraged to deal with it openly. The teacher and the researcher perhaps more openly modeled this learning to swim along with students because they were sometimes uncertain of what to do. Their level of uncertainty was often more pedagogic in the sense that they did not know how much to tell, direct or pull away. Both gradually learned with the students how to intervene and when. Acting from a position of advisor - facilitator - guide more than director, the teacher and researcher had to lessen or at times relinquish the role of provider of knowledge and become more of a questioner. By questioning students, they were forced to think seriously about what they were doing because if they did not they would not be able to solve the problem. This enabled them to know that they know.

Students in becoming knowers were challenged to become competent knowers who knew that they can find meaning for themselves not necessarily alone in silence but in constant conversations with others. They were also challenged to become knowers with ideas and opinions that needed to be heard. Teachers and researcher had to become good listeners to be able to listen and hear some of the soft hidden voices.

From this study, we have progressively modified and utilized three activities that can be used in high school chemistry to rejuvenate our chemistry curricula. These modified activities and the approaches used to teach them address more of the goals of science education. They more effectively addressed the attitudinal or predispositional science education goals that are otherwise difficult to teach from other traditional approaches. With this approach, the activities could also be extended to explicitly explore issues of the nature of science and method in science as well as the interrelatedness of science, society and technology. Table 8 summarizes the approaches and objectives of both the traditional and open-entry ways of teaching each of the open-entry activities. The iterative nature of designing and redesigning, creating and recreating, evaluating and reevaluating and synthesizing that was required throughout the investigation and with all the investigations enabled students to test themselves, build endurance, deal with their uncertainty, enhance their problem solving skills and increase their self-confidence. They engaged in tasks that traditionally are thought to be too difficult and complex for high school students, e.g., creating procedures and evaluating them. Student successfully developed criteria for evaluating and validating their science doing.

Traditional laboratory activities are often designed to remove major difficulties for students. This tends to make them recipe-like. From this study it is apparent that maintaining some of the difficulties and giving students some autonomy created opportunities for students to engage and learn meaningfully. Students were able to handle uncertainty and they learned to make decisions. In general, traditional laboratory activities are not modified by teachers because they are time efficient and they can fit within the normal school schedule. In general, traditional laboratory can be modified to make them more open-ended

Table 8

Open-Entry Laboratory Work in this Study

Activity/lab	Traditional approach[1]	Traditional objectives[2]	Open-entry approach[3]	Open-entry objectives[4]
Iodine clock	Teach the variables that affect reaction rate and complete a controlled experiment in a recipe-like fashion. (Often done as a traditional lab.)	To verify the effect of temperature, concentration and catalysis on reaction rates (and maybe to create the rate law for this reaction).	Assist students to: -design/ redesign an experiment -create/recreate the procedure -try/retry the skills -evaluate/synthesize	To engage students in meaning making in science by employing and evaluating personal designs, procedures and skills.
Pop-can cell	Demonstrate the cell concept with a potato clock, a grapefruit or a pop-can. (Not often done as a traditional lab.)	To create the concept that any two different electrodes with an electrolyte is an electrochemical cell.	Assist students to: -design/ redesign an electrochemical cell -try/retry the skills with a multimeter -evaluate/synthesize	To create a pop-can cell that meets the criteria (e.g., voltage, current or power) determined by the students themselves.
Electroplating	Teach the qualitative and quantitative aspects of electrolysis, but not often do an electroplating lab, due to difficulties.	To demonstrate/ verify that electroplating does occur—in whatever quality or quantity.	Assist students to: -design/ redesign an electroplating cell -try/retry skills with a multimeter and circuitry -evaluate/synthesize	To judge the quality of electroplating by different procedures and to create the best procedure available.
River project	Teach the use of water quality test kits to determine the quality of water in the river.	To determine quality (based upon required parameters) of water in the river.	Assist students to: -gather samples -use the test kits -report their results	To test the reliability, efficiency and validity of results obtained from water test kits.

Notes:

1. The traditional laboratory approach often emphasizes analysis and is very linear and singular.
2. The traditional objectives for laboratory work are most often to demonstrate/illustrate and verify concepts presented in the classroom.
3. The open-entry laboratory approach often emphasizes evaluation and synthesis and is very iterative.
4. The open-entry objectives for laboratory work are most often to engage students as knowers, to engage students in naturalistic scientific investigation, and to encourage students in personal meaning making.

This is done by modifying the components of a laboratory so that students are required to find out more information for themselves. In the Table 9 below a general scheme of how laboratory activities can be transformed, say, from closed cookbook type to open-ended to open-entry is presented. For instance, in this study all the open-entry activities we conducted students were required to develop a design and a procedure and also to select materials to use whereas traditionally students would be given all that information. Many of the traditional laboratory activities can be modified to become open-ended. There are, however, few traditional laboratory activities that can be modified to become fully open-entry.

The different activities among other things could be used to show the complex multi-dimensionality of chemistry. There is a need to explore and to gradually develop more open-ended and more open-entry type activities to be able to provide options for high school teachers and students to work with.

A balanced and progressive laboratory program would lead the students from closed to open-ended to open-entry investigations. All courses should have some of each. At higher levels more investigations should be open-ended and open-entry. Students should be prepared at one level before moving gradually to the next level.

Table 9 allows teachers/authors to see how they can convert one kind of laboratory activity into another kind, based upon what is given to or required of students. A balanced curriculum of laboratory work should be thoughtfully created with the ability and potential of students in mind.

Table 9

Components of a Laboratory Program

Processes	Closed	Open-ended	Open-entry
Purpose	Verify	verify/falsify	Falsify/create
Problem	G	G	G/R
Hypothesis	M	G/R	G/R
Prediction	M	G/R	G/R
Design	G	G	G/R
Materials	G	G	G/R
Procedure	G	G	G/R
Evidence	R	R	R
Analysis	R	R	R
Evaluation	M	R	R
Synthesis	N	M	R
Iterative	N	N	R

Notes.
G—given to the student
R—required of the student
M—may be required of the student
N—not required of the student
G/R—given to or required of the student

Implications for Practice

The teaching and learning of science is becoming more complex and this complexity requires practitioners to be proactive to be able to cope with and to address the demands emerging from this complexity. Research conducted in classrooms where this complexity is acknowledged and addressed may help other practitioners. This research acknowledges that different teaching positions as summarised in Table 10 have their place in teaching science. The emphasis suggested is the need for balance in terms of teaching approaches and the curriculum students engage. The following summary highlights areas that may be improved based of the findings of this research.

- This research assumes that the traditional and the constructivist positions are valid/useful components of a balanced instructional program
- This research shows the value of open-entry laboratory work as a component of an enactivist position
- Based upon this research, teachers should come to see the enactivist position as value-added to the traditional and the constructivist laboratory programs
- Enactivist laboratory work attends to the scientific attitudes listed in most curricula
- Enactivist laboratory work tests and reinforces the self-confidence of students
- Enactivist laboratory work facilitates creativity, evaluation and synthesis
- Enactivist laboratory work assists students to become independent problem-solvers/decision-makers
- Enactivist laboratory work allows students to match problems with solutions and solutions with problems

Table 10

Comparison of Teaching Positions in High School Science

Teaching positions	Teacher place and world view	Teaching possibilities	Teacher's view of curriculum and the body of science	Teacher's pedagogy and action	Nature of discourse and goals	Evaluation/ assessment
Traditional	in front of class an externally pre-given world	one correct scientific possibility	reflects the correct scientific world	preplanned presentation with teacher talk, reproduction and remediation	unidirectional, uniform conforming to one scientific view	prescriptive; teacher checks for, looks out for or listens for correct or best answer
Constructivist Emergence	in front of student or over the shoulder an internally constructed world view	a correct scientific outcome, an individual construction and a conceptual change	facilitates student's construction to match with scientific view by finding bits of appropriate curricula	set up context and facilitate individual constructions, discrepant events, cognitive dissonance, and testing personal hypotheses	supportive, focusing on logical understanding, and elaboration of abstract concepts using personal constructs	semi-prescriptive teacher listens to students' portrayals and supporting arguments and compares with existing body of science
Enactivist co-emergence	beside the student(s) a co-emergent world view a world view that includes/ embraces uncertainty	multiple possible scientific questions, answers and pathways teacher creates opportunities, keeps open and listens for new possibilities	curriculum is enacted, lived, complex and dynamic students co-participate in the contemporary practices and bring forth a world of scientific significance	co-emergent, context-bound, co-participation with students teacher invites creativity and evaluation and acts with students	interactive, exploratory, creative and explanatory bringing forth relations, coherences and worlds of significance with others	proscriptive; teacher listens with students to bring forth a world of scientific significance

The main focus in aiming at addressing all the science education goals is to increase students' scientific literacy. From this research, the enactivist approaches used in the open-entry investigations seemed to nurture and empower students in the science classroom so that they could leave the school system independent and able to engage in science and technology related societal issues.

Difficulties in Practice

Enactivist laboratory work requires a pedagogically and academically competent and confident teacher (the shortage of secondary chemistry and physics teachers and their replacement by others who may be less academically competent in these disciplines may be a road block for encouraging the enactivist laboratory work).

Teaching using this type of activities is not easy. Apart from open-mindedness, it requires confidence from the teacher. The teacher needs to have confidence that even though he or she may not be able to predict the outcomes of the interactions, with the guidance of the teacher's embodied ways of knowing, the existing and yet dynamic culture of chemistry, and the living in a community and besides knowers who participate with him or her in the processes of making meaning, new meanings and new worlds of chemistry can be brought forth. For beginning teachers the road might be a little steep since they often do not have the extended experience in the practice upon which to build their confidence in using this teaching approach. A possible dilemma that could arise in the present educational context is in terms of content. An experience I had was struggling with the engrained tendency of expecting the use of abstract concepts or theories as the framework or structure of teaching. For a discipline studied initially for purposes of mastery of content, teachers would need a paradigm shift in their pedagogy so that they can develop a deeper personal understanding of the nature of the discipline as well as the goals of teaching the subject. This is essential for teaching a science curriculum that integrates STS and teaches technological problem solving.

Co-designing a Curriculum

Engaging the different laboratory activities initially started for us all as doing a different kind of laboratory. We did not know what exactly we would learn from this research but we had confidence that we would learn something meaningful and useful about students' meaning making and about these laboratory activities. We did not envision an all encompassing emergence as we see now, even though from the enactivist perspective one would anticipate a bringing forth of new worlds of significance.

Although this study did not specifically aim at finding ways of transforming the curriculum, it is the students' articulated meanings and coherences brought to bear from their responses in class, in their written work and in the interviews that revealed the holistic personal understandings that emerged for them. Ursula, for instance, did not think she would study science at the university; however, her understanding of the nature of science and the contributions that people make to making science what it is was educative. A well rounded learner who knew clearly the role she played in these activities was brought forth.

Students' perceptions triggered for the teacher and me a new way of looking, an invitation to shift focus. Their views on the different laboratory activities allowed us, the teacher and me to re-view our perceptions of the investigations. I had not seen the possibility of the evolutionary trend that these could present until I did this research wrting. As I started engaging students' interactions, listening to what they said , sitting back and reflecting on my own thinking about what students said new ways of seeing continued to emerge. The cyclic revisiting of uncertainty and its effect on students confidence and ability to handle the uncertainty coupled with the emergent evolutionary trend presented by this sequencing of the activities also pointed us to a possibility of a laboratory curriculum with a defined evolutionary purpose.

Whereas many laboratory programs include a variety of laboratory activities, there has not been much attention paid to an overarching evolutionary purpose characteristic of a curriculum. I mentioned in chapter one that the Alberta elementary science program features some technological problem solving activities but that they seem to fizzle out in the middle school and if any are done at all in high school, they are done as separate unrelated activities. It might perhaps be that in developing the science curriculum we need to look at developing a science laboratory curriculum with a defined and balanced purpose to be able to help students focus on all the goals for science education.

Researching as a Re-Searching for Self

When we conduct research we not only learn about doing research we often learn about ourselves. We learn to identify what works for us in the research and also what does not. Therefore from the process of doing this research I will discuss some of the things I learned.

A Co-emergent Enactivist Learner-Researcher

Research suggests that the conceptual turning point regarding cognition including learning and knowing requires us to completely shift our understanding of cognition from the concept of cognition as a commodity to be had and to be measured with paper-pencil tests and more to a relational, more qualitative aspect that involves a high degree of adaptability and of functioning adequately in a given domain or context. Cognition from this view is effective action of a living being in its environment.

From a researcher's perspective enactivism offers us tools with which we can come to a different understanding of the learning-teaching processes in the sciences. It offers us ways of perceiving research where we do not focus only on trying to establish causality. Instead we look for relationships from which we can develop coherences and patterns of coherences that enable us to explain in a broader sense our experiences of phenomena. From this research, we know, for instance, that the ways in which we related to students changed what they learned about themselves and about their world. In turn, we learned that we can develop a different understanding and perhaps be better equipped to help students by listening and paying attention to their ways of acting, knowing part of their history and trusting that they can, within this chemistry classroom community, take responsibility for their own learning. By creating this learning environment we offered them a space to interact, and live consciously and responsibly with others. This offered us room to use a variety of approaches to the research process. It enabled us to use combinations of qualitative descriptive and interpretive methods as well as quantitative descriptive methods. From a researcher's point of view one is not limited to either one or the other. It also offers us a variety of interpretive tools.

Researcher Participation

In research endeavors that aim at understanding human processes, a researcher can not exist outside the processes under investigation and hope to gain a meaningful understanding, assuming that they do not influence these processes or that (s)he is not influenced by the research. From the enactivist perspective, we understand that the very act of researching phenomena, changes both researcher and phenomena. Through our interactions in this research I did not only change to become a better recorder or a better interviewer but I changed in many ways some of which I am not able to identify. I know I listen differently and I perceive the world of high school chemistry differently. In their interactions, researchers become part of the very context that transforms the phenomena under investigation. Jager and Irene, for instance, allude to this transforming act of living and interacting together. The challenge for a researcher is to recognize and acknowledge his or her role in the process. Through our interactions with phenomena we become structurally coupled to the phenomena and we become transformed in the process while we also become agents of transforming phenomena. In a classroom situation the researcher can play various roles, including being a learner, a resource person, a tutor and inevitably a teacher as he or she works beside the students. This puts an onus on the researcher to work with students creating a space for them in the process, as legitimate others; a process Maturana (2000) calls **love**.

Interpretive Tools for Complex Learning Process

Enactivism points us to many contextual aspects of the learning-teaching activity that are often taken for granted in evaluating students' knowing. It offers interpretations and explanations about relations that may enable us to see how certain phenomena and processes are possible. It does not offer explanations in the form of causes. In the learning-teaching processes, enactivism invites us to look, listen, and feel for the student and consequently to act ethically in creating spaces for students to learn with us and beside us.

Representation of Processes

Representations can be problematic for a reader depending on the reader's perspective. They can be read and interpreted from one extreme as finished products and from the other extreme as unfinished business. Although the two extremes may seem to contradict each other they are not mutually exclusive. They are two sides of one coin because in one way by the time this document is bound and submitted to graduate studies, it will be out of my hands as an artifact, a product that I can not change. However, it will also remain unfinished because different readers including myself can and will continue to interact with it, modifying the ideas presented, perhaps testing and evaluating them in different settings and continuing the iterative cycle of learning. For me it will always change as it has progressively changed me. It is on going research, research about me and my environment.

To this effect I offer my positioning as the one offering these interpretations which will continue to be re-interpreted by myself and others for whom this dissertation will offer perturbations or triggers. The accounts and descriptions rendered in this dissertation are my interpretation of what I saw, heard, felt, and said as a participant in the classroom and in the laboratory activities that we investigated. The meanings thereof are meanings that I made about students' meaning making. In describing and articulating what I felt were salient features of the interacting-in-open-entry investigations I tried to stay as true to students' description as possible so as not to obscure their meanings as they too were part of this research. I used triangulation of information. In this triangulation I depended on what students said and did about their interactions. I used as much as possible students' words. The examples I gave in most cases if they were not part of the open-entry laboratory investigations; I used the speaker's word to say for me what I wanted to say.

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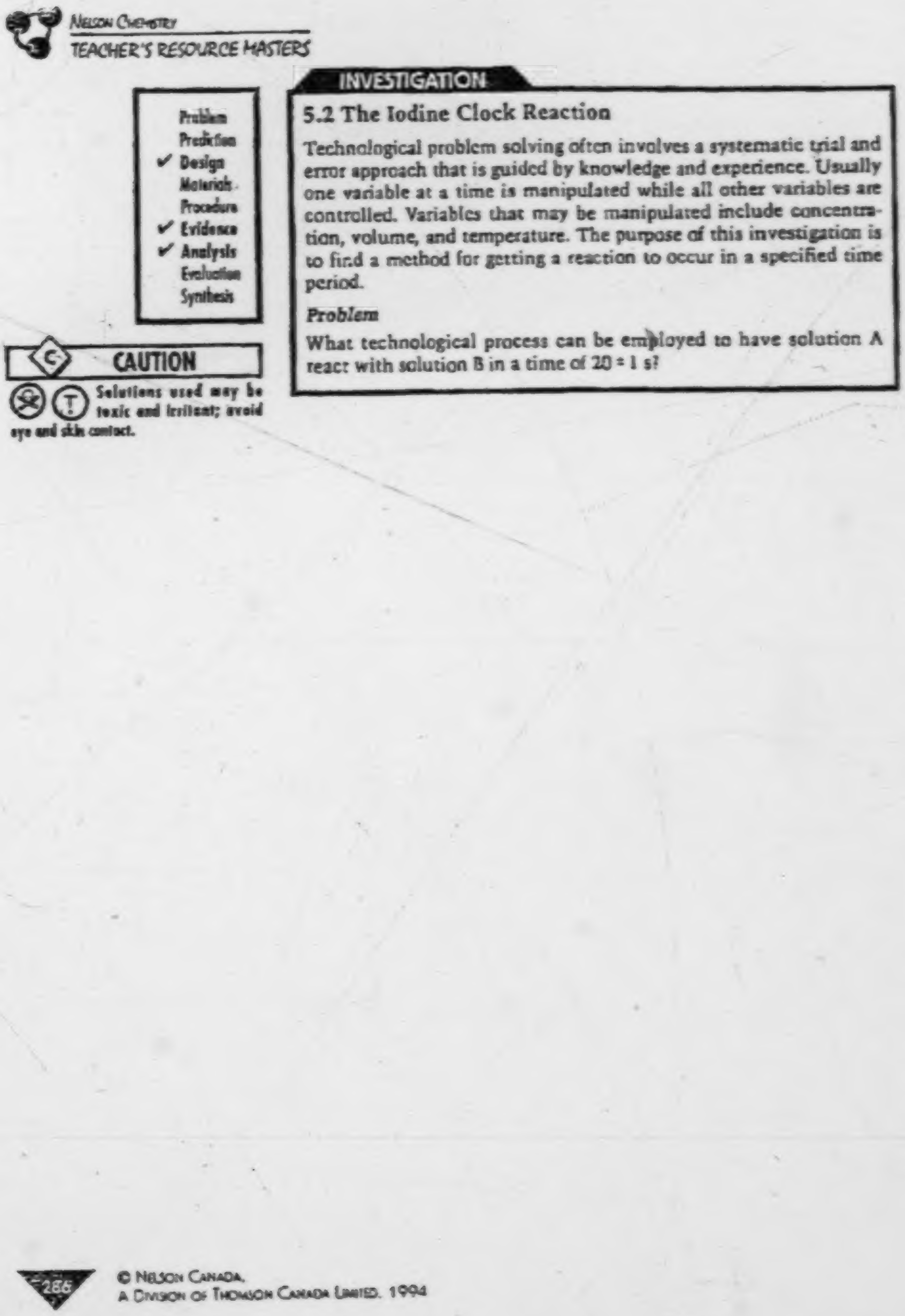
APPENDIX A

HANDOUTS OF THE THREE UNMODIFIED LABORATORY INVESTIGATIONS

Appendix A

Handouts of the Three Unmodified Laboratory Investigations



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TEACHER'S RESOURCE MASTERS

- Problem
- Prediction
- ✓ Design
- Materials
- Procedure
- ✓ Evidence
- ✓ Analysis
- Evaluation
- Synthesis

CAUTION

Solutions used may be toxic and irritant; avoid eye and skin contact.

INVESTIGATION

5.2 The Iodine Clock Reaction

Technological problem solving often involves a systematic trial and error approach that is guided by knowledge and experience. Usually one variable at a time is manipulated while all other variables are controlled. Variables that may be manipulated include concentration, volume, and temperature. The purpose of this investigation is to find a method for getting a reaction to occur in a specified time period.

Problem

What technological process can be employed to have solution A react with solution B in a time of 20 ± 1 s?

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☐ Problem
✓ Prediction
☐ Design
☐ Materials
✓ Procedure
✓ Evidence
✓ Analysis
✓ Evaluation
☐ Synthesis

CAUTION

Be careful when handling acidic and basic solutions used for electrolytes, as they are corrosive. Wear eye protection and work near a source of water. Some electrolytes may be toxic or irritant; follow all safety precautions. Avoid eye and skin contact.

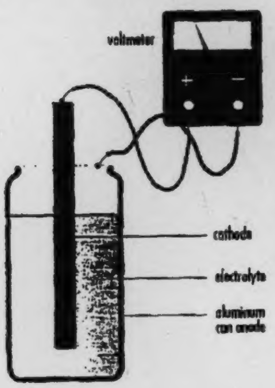

Figure 13.7
An aluminum-can cell is an efficient design since one of the electrodes also serves as the container.

INVESTIGATION

13.2 Designing an Electric Cell

The purpose of this investigation is to use everyday materials to simulate the technological development of an electric cell in which an aluminum soft-drink can is one of the electrodes (Figure 13.7). The other electrode is a solid conductor such as graphite from a pencil, an iron nail, or a piece of copper wire or pipe. The electrolyte may be a salt solution or an acidic or basic solution. Although many characteristics of a cell are important for an overall evaluation of performance, only one characteristic, voltage, is investigated here. Check with your teacher if you wish to evaluate other designs and materials.

Problem

What combination of electrodes and electrolyte gives the largest voltage for an aluminum-can cell?

Prediction

Experimental Design

(a) Using the same electrolyte and aluminum can as the controlled variables, two or three different materials are employed as the second electrode. The voltage of each cell is measured.

(b) Using the same two electrodes as the controlled variables, two or three possible electrolytes are tested. The voltage of each cell is measured.

(c) Additional combinations are tested, based on the analysis of the initial trials.

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- ■ Problem
- ☑ Prediction
- ■ Design
- ☑ Materials
- ☑ Procedure
- ☑ Evidence
- ☑ Analysis
- ☑ Evaluation
- ■ Synthesis

CAUTION

Copper(II) sulfate is toxic and irritant. Avoid skin and eye contact. If you spill copper sulfate solution on your skin, wash the affected area with lots of cool water. Remember to wash your hands before leaving the laboratory.

INVESTIGATION

13.7 Copper Plating

The purpose of this investigation is to determine the best procedures for plating copper onto various objects. Evaluate both the process and the product.

Problem

Which procedure causes a smooth layer of copper metal to adhere to a conducting object?

Prediction

Experimental Design

A small metal object, such as a spoon, a key, or a piece of metal, is carefully cleaned. A 0.50 mol/L copper(II) sulfate electrolytic cell that uses an inert electrode as the anode is constructed. The object to be plated is used as the cathode (Figure 13.29). Potentially relevant variables are identified and systematically manipulated. The success of the plating is evaluated by the appearance of the object and by polishing the plated object with steel wool to test adherence of the copper coating.

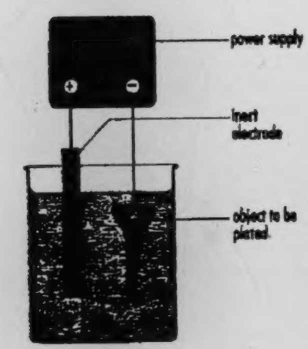

Figure 13.29
An electrolytic cell for copper-plating small objects.

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APPENDIX B

IODINE CLOCK REACTION: TWO TRADITIONAL VERSIONS

Appendix B

thermometer (-10 to 110°C)

Solution # 1: potassium iodate 0.02 mol/l; KIO$_4$ [4.3 g/l]
Solution #2: thiosulfate starch solution.
Preparation of solution #2: Heat about 3/4 liter of water to boiling. Add 4 g soluble starch. Stir until dissolved. Let cool. Add 0.2 g sodium thiosulfate, Na$_2$S$_2$O$_5$. Add 5 ml 1mol/l H O$_4$. Dilute to 1 liter.

A slightly different and older version of the iodine clock reaction copied from the Journal of Chemical Education under A Chem Ed tested demonstration entitled, A Versatile Clock Reaction is presented below.

B. A Versatile Clock Reaction (Dye, 1950)
Preparation

Obtain four beakers or large test tubes, 2 - 100 ml graduates, a thermometer, burner or hot plate, timer, and prepare the following three solutions:

Solution A:

50 g of potassium iodide, KI
90 mg sodium thiosulfate, Na$_2$S$_2$O$_5$
10 ml of 5% soluble starch in sufficient water to make 1 liter of solution

Solution B:

5 g of sodium peroxysulfate, Na$_2$S$_2$O$_8$ in sufficient water to make 1 liter of solution. If all of the solid can not bedissolved, pou off the clear saturated solution.

Catalyst:

A small amount of dilute aqueous solution of FeSO$_4$ with CuSO$_4$ in a dropping bottle.

Demonstration

1. Mix equal volumes of solutions A and B and note time for appearance of the blue color.
2. Mix one volume of A plus one-half volume of B plus an equal volume of water. Note time for appearance of blue color.
3. Mix equal volumes of A and b, one of these solutions being chilled or heated 20° below or above room temperature (this results in an average temperature change of 10°). Note time for appearance of blue color.
4. Mix equal volumes of A and B with one drop of catalyst added to B. Note time for appearance of blue color.

Remarks

This demonstration is most dramatic if solutions A and b are prepared and given to four separate students who mix them simultaneously in front of the class. This clock reaction has the advantage over others in that it is possible to demonstrate all of the common factors discussed in connection with the speed of reactions, temperature, concentration and effect of a catalyst. The accompanying footnote specifies that the demonstration was rewritten from Steinbach, Otto F., and King, Cecil V., "Experiments in Physical Chemistry," American Book Co. 1950, p. 220.

Iodine Clock Reaction: Two traditional versions

A. The effect of concentration and temperature upon reaction rates

Purpose

1. To empirically determine the effect of concentration of reactants on the rate of chemical reaction.
2. To empirically determine the effect of temperature on the rate of a chemical reaction
3. To provide experience in order to gain insight into what is meant by empirical evidence

Pre-demo Discussion:

Evidence from the first part of Unit M indicated thatthe spontaneity of some redox reactions can be accurately predicted.However,redox reactions,like many chemical reactions,can be spontaneous but so slow that no change can be noticed except over a long period of time.The rusting of iron is a good example of a slow change caused by a redox reaction.Clearly the rate of reaction is an important part of any discussion of chemical change,but theories predicting rate of reaction have been of limited success.In most cases, information on rates or reaction kinetict is obtained empirically by experiment .The following demonstration illustrates some of the factors that affect the of chemical reactions.Note that in this demostration actually concentrations or temperatures may not always be measured since only qualitative relationships are being sought. The reaction occurring in Demo MI is called the Iodine Clock Reaction and can be represented as follows;

$$2IO_{3(aq)} + 5HSO_{3\text{-}(aq)} \qquad 5SO_3{}^{=}{}_{(aq)} + 3H^{+}{}_{(aq)} + I_{2\,(aq)} + H_2O_{(l)}$$

Before the $I_{2(aq)}$ product can react with the starch which is present, it is consumed by any unreacted HSO_3- according to the equation:

$$2I_{2(aq)} + HSO_{3\text{-}(aq)} + H_2O_{(l)} \qquad 2I_{\text{-}(aq)} + SO_4{}^{=}{}_{(aq)} + 3H^{+}{}_{(aq)}$$

However, when all of the $HSO_{3\text{-}(aq)}$ has been used up, the $I_{2\,(aq)}$ accumulated and reacts with the starch present in the solution. The resulting intense blue colour, which is detectable at very low concentrations, indicates that the reaction has consumed all of the $HSO_{3\text{-}(aq)}$ that was initially present. In the first part of the demonstration the temperature and the $HSO_{3\text{-}(aq)}$ concentrations, other than that of the are kept constant. The effect of varying concentrations on reaction rates will be determined by noting the time it takes to complete the reaction of the $HSO_{3\text{-}(aq)}$. In the second part of the demonstration, only the temperatue is varied to determine whether or not the reaction rate is effected.

Equipment needed:
test tube rack
12 ea. 25 x 200 mm test tubes
100 mL beaker
3 ea. 10 mL graduated pipets
pipet bulb
3 ea. 500 mL beakers
Stopwatch
ringstand
Iron ring
Wire gauze
Bunsen burner
Ice (in insulated container)

APPENDIX C

STUDENTS' SAMPLE LABORATORY REPORTS

Appendix C

Students' Sample Laboratory Reports

Chemistry 30E, period 4
Nov. 15/97.

Investigation 5.2
The Iodine Clock Reaction.

Investigation 5.2 - The Iodine Clock Reaction.

Problem:
What technological process can be employed to have solution A react with solution B in a time of 20 ± 1 seconds?

Experimental Design:
Of solution A and solution B, one will be chosen to vary in volume and one will remain constant. This will depend on what effect each solution will have on thre reaction rate. For example, if the volume of solution A is greater than that of solution B and the reaction is faster than if the volumeof solution B is greater than that of solution A, it would be wise to say that more of solution A will help to quicken the reaction and that more of solution B will help to slow down the reaction. Once this is determined, the manipulated solution will be varied when mixing to the constant until a reaction time of 20 ± seconds is reached.

Evidence:

Reaction Time of Solutions A & B Taken at the End of the Reaction When the Volumes of the Two Solutions are Manipulated.

TRIAL	VOLUME A (ml)	VOLUME B (ml)	TIME (s)
1	10	10	9.83
2	8	10	9.45
3	10	8	9.95
4	10	5	14.91
5	10	3	21.86
6	10	3.4	21.03
7	10	3.8	18.26
8	10	3.6	12.06
9	10	3.6	15.09
10	10	3.6	17.57

Reaction Time of Solution A & B taken at the Beginning of the Reaction When the Volumes of the Two solutions are Manipulated.

TRIAL	VOLUME A (ml)	VOLUME B (ml)	TIME (s)
1	10	10	6.85
2	10	2	12.05
3	10	1	9.81
4	5	10	7.18
5	3	10	7.27
6	1	10	8.08
7	1	5	9.20
8	2	5	6.07

Analysis:

Based on the evidence gathered, the technological process employed did not accurately have solution A react with solution B in a time of 20 ± 1 seconds. Since the results recorded are not consistent we can not believe that they are accurate. We are not able to rely on them, notwithstanding some of the results indicate that the reaction time was indeed 20 ± 1 seconds. In our first procedure included the following steps:

1) Obtain at least 50 ml of solution A and at least 50 ml of solution B in separate beakers.

2) Measure 10 ml of each solution in two separate 10 ml graduated cylinders.

3) Time the reaction with a stop watch by starting the watch when the two solutions come into contact and stopping the watch when the reaction is over. (solution turned completely dark blue) .

4) Record the time.

5) Now determine which solution speeds up the reaction and which solution slows down the reaction first by mixing 10 ml of solution A and 8 ml of solution B.

6) Time the reaction in the same manner and record the results.

7) Now mix 10 ml of solution B with 8 ml of solution A.

8) Time the reaction in the same manner and record the results.

9) Now by comparing the results thus far, determine which solution speeds up the reaction time and which solution slows down the reaction time. Once determined decide which solution should be kept constant and which solution should be the manipulated variable.

10) Vary the volume of the manipulated variable to the necessary volume until the reaction time reaches a time of 20 ± 1 seconds.

11) Once the necessary volume of each solution is determined to make a reaction time of 20 ± 1 seconds, be sure to test the volumes again several times to ensure accuracy.

In our first experimental design we found that more of solution A and less of solution B sped up the reaction time when measured from when the two solutions come into contact until the end of the reaction. In finding this, we decided to keep solution A constant at a volume of 10ml and lessen the volume of solution B beginning at 8 ml then down to 5 ml then 3 ml. At 3ml we found that we had gone over 20 ± 1 seconds, so we used the eye dropper to increase the volume of solution B to 3.4 ml. This was still over 20 ± 1 seconds of reaction time so we tried increasing the volume of solution B to 3.8 ml. We got a result of 18.26 s which is less than 20 ± 1 seconds so we tried decreasing the volume of solution B to 3.6 ml to see if we could get a reaction time of 20 ± 1 seconds. At this point the results began to stray from its pattern of an increase reaction time with a decrease of the volume of solution B. If the reaction time of the solutions was 21.03s with 3.4 ml of solution B and then 18.26s with 3.8 ml of solution B it would not make sense if the reaction time was 12.06s with 3.6 ml of solution B. To make sure the result was accurate, we tested the reaction time of 3.6ml of solution B with 10 ml of solution A two more times. The results were once again inconsistent with the pattern of an increased reaction time with the decrease of the volume of solution B. As these results were obviously not reliable, we concluded that our method of timing the reaction by stopping the watch at the end of the reaction was not dependable. Therefore, we attempted an alternative experimental design which included the following procedures:

1) Obtain at least 50 ml of solution A and at least 50 ml of solution B.

2) Measure 10 ml of each solution in two separate 10 ml graduated cylinders.

3) Time the reaction using a stop watch by starting the watch when the two solutions come into contact and stopping the watch when the reaction begins. (solution begins to turn blue)

4) Record the time.

5) Now determine which solution speeds up the reaction time and which solution slows down the reaction time first by mixing 10 ml of solution A and 8 ml of solution B.

6) Time the reaction in the same manner and record the results.

7) Now mix 10 ml of solution B with 8 ml of solution A.

8) Time the reaction in the same manner and record the results.

9) Now by comparing the results thus far, determine which solution speeds up the reaction time and which solution slows down the reaction time. Once determined decide which solution should be kept constant and which solution should be the manipulated variable.

10) Vary the volume of the manipulated variable to the necessary volumes until the reaction time reaches that of 20 ± 1 seconds.

11) Once the necessary volumes of each solution is determined to make a reaction time of 20 ± 1 seconds, be sure to test the volumes again several times to ensure accuracy.

In the results of our our second procedures we found that once again our results were inconsistent. They did not remotely follow the pattern of our first experiment at all. The reaction times were way off. In procedure 1 we recorded a reaction time of 9.83s with 10 ml of both solution A and B, but in procedure 2, we recorded a reaction time of 6.85s with the same volume of both solutions. Since the results were invalid and not reliable in the first experiment, we decided not to compare the results of the two procedures in great detail and to continue on to see if another pattern would develop. We found the pattern of the first procedure was the opposite pattern of this second procedure. We found that a constant volume of solution B at 10ml and a decreasing volume of solution A gave faster reaction times. This pattern like the first one was not consistent either. Since the evidence gathered is all inconsistant and hence not reliable this supports the conclusion of our analysis that the technological process we employed did not accurately have solution A react with solution B in a time of 20 ± 1 seconds.

June 9th, 98 partner:
Chemistry 30E period 2

Investigation 16.2 - Designing an Electric Cell

The purpose of this investigation is to use everyday materials to simulate the technological development of an electric cell in which an aluminum soft drink can is one of the electrodes.

Problem: Which type of electrolyte will combine with aluminum and carbon electrodes to produce the highest voltage?

Prediction: According to Nelson Chemistry, commercial batteries combine aluminum and carbon electrodes with a basic electrolytes to produce a reasonably high voltage. Considering $HCl_{(aq)}$, $NaOH_{(aq)}$ and $NaCl_{(aq)}$ as possible electrolytes, $NaOH_{(aq)}$ would likely produce the highest voltage due to its basic properties.

Experimental Design: Three different cells are created using aluminum soft-drink cans and carbon rods as the two electrodes. The three different electrolytes $HCl_{(aq)}$, $NaOH_{(aq)}$, and $NaCl_{(aq)}$ are used and the voltages are measured using a voltmeter.

controlled variables: electrodes, voltmeter, structure of cell, volume of electrolytes
manipulated variables: electrolyte
responding variables: voltage

Materials:

- 3 355mL soft-drink cans with tabs removed
- 118mL of $HCl_{(aq)}$
- 118 mL of $NaOH_{(aq)}$
- 118 mL of $NaCl_{(aq)}$
- steelwool

Inv. 16.2 (cont'd)

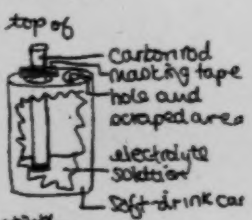
(materials cont'd):

- paper towels
- lab apron
- safety goggles
- key or small, sharp metal object
- masking tape
- voltmeter in good working condition (test with a commercial drycell).
- 3 150mL graduated cylinders
- 3 carbon/graphite rods
- acetone

SAFETY: Wear lab apron and safety glasses.

Procedure:

1. Thoroughly rinse out the Inside of the can and wipe the top of the can with acetone to expose the aluminum and allow conduction. Use a key or sharp metal object to scrape away any remaining chemical film from the top of the can.
2. Puncture a small hole in the part of the top of the can that no longer has a film over it.
3. Clean the carbon rods ~~with~~ and the top of the can with steel wool.
4. Fill $\frac{1}{3}$ of each soft drink can with a different electrolyte (approx. 118mL) solution, one HCl(aq), one NaOH(aq) and one NaCl(aq).
5. mouth of the soft-drink can with masking tape. Put masking tape across the the top of the carbon rod so it will not fall into the can.
6. Place the rod in the can, ensuring that part of it is in the electrolyte solution but it is not touching the bottom or sides of the can. (See diagram to right).
7. Test the area around the small hole for conductivity by setting the voltmeter to ohms (Ω). Set the voltmeter to "volts-direct current" (VDC) and range 4V.
8. Place the negative electrode of the voltmeter in the small punctured hole and touch the positive electrode to the top of the carbon rod. Record the voltmeter readings.



Inv. 16.2 **Evidence:**

The effect of various electrolytes on voltage:

electrolyte (~118mL)	Voltage (VDC)
$NaOH_{(aq)}$	1.221
$HCl_{(aq)}$	0.935
$NaCl_{(aq)}$	0.510

Slight fluctuations in the voltage readings of approximately ±0.005V were observed before and after the electrodes touched the electrodes of the battery. The values recorded above were the most consistent readings.

Analysis: According to the evidence, the cell containing the ~~el~~ sodium hydroxide electrolyte produced the highest voltage. Therefor the most effective electrolyte, of those tested, to combine with aluminum and carbon electrodes is $NaOH_{(aq)}$.

Evaluation: The ~~[illegible]~~ procedure and design are judged to be adequate because they were simple and the investigation ran smoothly. The skills are judged to be adequate because they are not complicated or difficult to perform.

The design of the cell itself had many features that made it effective. The small hole used to hold the negative electrode was particularly effective because it allowed the investigator to ~~[illegible]~~ use one hand to touch the positive electrode to the carbon rod and keep the other hand free. The use of masking tape to cover the drinking hole and to ~~[illegible]~~ keep the carbon rod from touching the bottom effectively prevented the carbon from contacting the aluminum. A difficulty with the materials was the enamel sprayed on the inside and top of the can by the factory, preventing the aluminum from being easily exposed. The ~~[illegible]~~ key effectively removed most of the enamel.

Inv. 13.7 Copper Plating

Station: Partner:
Block: 3/4 Date of Inv: Apr. 11

Purpose: To determine the best procedures for plating copper onto various objects.

Problem: Which procedure causes a smooth layer of copper metal to adhere to a conducting object?

Prediction:

$$Cu^{2+}_{(aq)} + 2e^- \longrightarrow Cu_{(s)}$$

2.0 min
2.0 A
9.65×10^4 C/mol

m
63.55 g/mol

$$n_{e^-} = 2.0\frac{C}{s} \times 2.0\,min \times \frac{60\,s}{min} \times \frac{mol}{9.65\times10^4\,C}$$

$$= .0025\,mol$$

$$n_{Cu} = .0025\,mol \times \frac{1}{2} = .0012\,mol$$

$$m_{Cu} = .0012\,mol \times 63.55\frac{g}{mol} = .079\,g$$

According to the stoichiometric method and the laws of electrolysis, the best process is plate .079 g with 2.0 amps for 2.0 min.

Design: A small metal object is carefully cleaned. A 0.50 mol/L copper(II) sulfate electrolytic cell that uses an inert electrode as the anode is constructed. The object is to be used as the cathode. Potentially relevant variables are identified and systematically manipulated. The success of the plating is evaluated by the appearance of the object and by polishing the plated object with steel wool to test adherence of the copper coating.

Materials: Safety glasses
Lab aprons
Power supply
Small metal object
Steel wool
0.50 mol/L of copper(II) sulfate
Inert electrode (carbon rod)
Clock
150 mL beaker
Connecting wires

Procedure:
1) Carefully clean metal object with steel wool
2) Connect metal object to the connecting wire of the negative side of the power supply.
3) Connect carbon rod to the connecting wire of the positive side of the power supply.
4) Place carbon rod and metal object into copper(II) sulfate solution and time length to plate.

Evidence:

	Trial 1	Trial 2
Amps (A)	2	2
Time (min)	2	5
Results	Copper solid came off, pieces left on	Copper solid mostly stayed on, few bare spots

Analysis: According to the evidence, the best method to plate an object is 2 amps for 5 min.

Evaluation: The design was adequate and the procedure was adequate as well. The experiment seemed easy enough to allow little error. The plating of the metal cross was successful so the prediction can be verified.

APPENDIX D

SAMPLES OF THE STUDENTS' REFLECTIVE NOTES

Appendix D

Samples of the Students' Reflective Notes

Reflective Notes: Iodine Clock Reaction: Folder #2

I felt that the lab was fun and that it develop critically thinking skills on how to solve a problem. However I felt that the equipement used was not precise enough to yield reliable results. The quantities or reactants were to small and thus allowed for great uncertainty. Large amounts should have been used. I felt that the easiest variable to control was the concentration of the reactants. Another solution to these problems of uncertainity could be to add a catalyst. And you say that will just speed up the reaction. I answer this question by saying that speeding up the reaction rate allows for more water to be used in the dilution process. The greater amount of water allows for greater accuracy. And those are my feelings.

It's difficult to get accurate and precise results when carrying out such experiments. Nevertheless, it was fun and I had a nice time mixing the solutions many times in order to get to a consistant result and it was an experiment involving as if trial-and-error.

I found that the lab was pretty frustrating at times. We would often have a volume that would give us a time close to 20 ± 1 s, but not close enough. Then we kept having to change our volumes to try and keep getting closer to the needed time. Also, we tried to repeat the test when we thought we had the correct volumes—but we didn't get very consistent results.

But, it was interesting to see the effect that a change in volume of each solution had on the time of the reaction—it was often not what we expected. Often we thought a particular change would speed up the reaction, but it really slowed it down.

I thought that this lab was much more difficult than our ordinary labs, because of the lack of procedure. Without a detailed, step by step, procedure, there is more room for error. However, this lab was also very interesting. There was much more freedom, in terms of what we could do. Overall, I liked the lab and enjoyed making our own procedure for our unique lab.

I really enjoy the lab. I enjoy manipulating variable, so that I can experiment my so-called "chem knowledge". As well, I like it when Mrs. P questions my explanation for my manipulation because it seems like I am a really "professional" chemist. I hope we do more of this labs.

- I loved every moment of it!
- A perfect KODAK moment!
- It was fun because we got to experiment freely using our own procedure and brains.

So many variables were difficult to control, making the lab a bit frustrating at times.

An open ended lab lives or dies by the success achieved by the student. If the experiment is easily achieved, then the emotional stability of the student is buoyed. However, it can be very frustrating if the experiment is difficult. For example, the inability of the stopwatch to go off at the most important trial is frustrating, as is the inability to quickly get an accurate volume of a solution. Basically these experiments require patience, perserverence, and patience.

Reflective Notes: Electroplating: Folder #4

Before I went to do the experiment, I assumed I'd be manipulating the current and time (high current/less time). Once I tried that in the lab, the key became overplated; the surface was rough, the color of the key was black. Then I decided to dilute the solution and poured 40 mL of water to 60 mL of the $CuSO_{4(aq)}$ solution. The end results were just as I hoped. After I finished the lab, I was glad ________ & I finished first and proceeded with excellent results.

According to the procedure used, this was not that difficult because the first trial produced a smooth layer but connecting the wires was difficult. This plating was efficient and simple.

Before working on this lab, I have no idea about which variables can make out the best procedures for plating copper.

During this lab, the power supply has some problem. It can't give out any voltage in it.

After this lab, although I have no idea on the best procedures, but I know voltage, current, object and conceration is important variables.

The lab wasn't too bad, the only part that was confusing was the setting up of the cell. There were alot of wires, but once that was straightened out it was alright. The actual plating was not difficult.

At the beginning of the investigation we had planned to manipulate the voltage, upon finding difficulty in this we had to change our entire procedure. More time to perform the investigation would have gave us a greater confidence in our results and would have given us a chance to manipulate other variables which would've aided us greatly in trying to answer the problem. It also would've been useful if we has power supplies that worked as this slowed down our progress greatly.

This lab, I found it to be a fun and learning experience. You didn't really know what you were doing at first, but about halfway through you already knew what your supposed to do, and then you start making up ideas and things you want to manipulate and control, and it's up to you. It your decision. The fun part was you didn't really know for sure if you've got the right copper plated color, and maybe you've got the wrong color, then you knew something was wrong in the connections of the wires. So then you had to start al over agian. But at the end we found the right perfect color.

From my perspective I did not enjoy this lab, as it was very frustrating. First we could not get a power supply that worked. Then when we found one that worked, there was way too many volts. The dimmer switch did not help either. I was glad when the class ended because this lab was not meant to be done by me.

APPENDIX E

PERMISSION LETTER

Appendix E

Permission Letter

University of Alberta
Edmonton
Canada T6G 2G5

Department of Secondary Education
Faculty of Education

January 29th, 1997.

Dear Parent or Guardian,

We are interested in studying the ways students learn chemistry in schools. Dr. Chem 30 classes provide instructional and learning activities suitable for our research. The results of our study will inform teachers and researchers in science education about the nature of student learning in chemistry.

During the study your son or daughter will be observed along with other students as they work on their required chemistry activities. We will be present in the classroom on the average of two to three times a week for an initial period of eight weeks beginning in February 1997. On selected occasions your son or daughter will be invited to comment on his or her learning experiences and the understandings which develops through interviews and small group discussions. We are planning to video-tape and audio-tape these activities and conversations in order to ensure the accuracy and authenticity of the information we gather. Occasionally we may find it useful to copy a sample of written work. We will ask for your son's or daughter's permission on each such occasion. Video/audio tapes involving your son or daughter and/or copies of their work will be kept anonymous and confidential and will be used only for the development and interpretation of our research.

Our presence in the classroom will not affect your son's or daughter's grades in any way. All students understand that their participation in any portion of this project is voluntary and that they are under no obligation to interact with us if they do not wish to do so at any time. We would be pleased to answer any questions that you may have at any point during our project. We are all experienced chemistry teachers, and will assist the students in achieving as well as they possibly can in their chemistry course. Please contact us by phone or fax.

Thank you in advance for giving consent for your son or daughter to participate in our study.

Yours sincerely,

Ms. Sentsetsa Pilane	Dr.	Dr.
Ph D student	Professor of Science Education	Chemistry Teacher.

Research Participation Consent Form for Parents or Guardians

Please complete the appropriate blank space. Detach at the dotted line above and return by February 10th, 1997.

Yes. I hereby give permission for my son/daughter(name)____________________________ to participate in the Chemistry learning study with _________, ___________ and Sentsetsa Pilane starting February 1997. The investigators may audio-tape and video-tape, interview my son/daughter during the research period.

No. I do not wish to have my son/daughter(name)____________________________ included in the research project.

Signature________________________ _____ Date

APPENDIX F

QUESTIONS THAT GUIDED MY INTERVIEWS WITH STUDENTS

Appendix F

Questions That Guided My Interviews With Students

Some discussion questions about students' exeperiences of open-entry investigations.

1. What did the series of open-entry activities have for you in general?
2. What did you learn from doing these laboratory activities?
3. What kinds of knowledge did you bring say, for instance, with the iodine clock reaction or the pop-can cell activity?
4. What assumptions did you have to make regarding the activity?
5. Did you think of ways you could test your assumptions as you worked through the activity?
6. How certain were you in your procedures from one step to another?
7. Remember Dr. M. Kept saying, from the very first activity that "it is a work in progress - you report where you are. You could even change the question or problem statement to reflect where you are." What did that mean for you?
8. Was the instrumentation used in the activities ever a concern to you?
9. If you were to go on with the research on any of the activities, where would you take it?
10. What kinds of questions would you want to find answers for?
11. Did the activities meet your expectations of what it means to learn and do chemistry?
12. What did you value most from your experiences of open-entry activities?
13. What was least valuable?